11th International Congress on Engineering, Design and Manufacturing, Sustainability and Resilience Approach
About Congress
Barcelona is ideal for international researchers that need a short rejuvenating break away from their university campus. The city is a banquet for all the senses, though perhaps mainly for sight. Not far behind are the pleasures of the palate. The air temperature is almost always about right, more and more streets are pedestrianized. Every now and then the fragrance of the sea in the port or in Barcelona reminds you that this is, after all, a giant seaport and beach city, with an ancient Mediterranean tradition that is, at the outset of its third millennium, flourishing and bewitching visitors as it has for centuries. Today new architecture and design including some of Europe’s hottest new fashions in hip boutiques provide the city with an exciting effervescent edge.

The Congress provides three days focus on the engineering, design and manufacturing informatization that are the basis for the information and manufacture. The theme is engineering, design and manufacturing informatization featuring invited speakers who will further explore this topic that is so significant in these fields.

ICEDM2016 invites you to showcase presentations, from the most diverse countries and cultures, to promote growth in research methods intimately related to Agricultural Sciences, Food and Environment. Our editorial board invites abstracts, papers, and proposals in three tracks.

The accepted papers will be published by International Leading Publishers (on process of agreement) or Publishers of International Society of Communication and Development among Universities and also submitted to SCOPUS, EBSCO, and Thomson Reuters Conference Proceedings Citation Index – CPCI (ISI Web of Science) for evaluation for inclusion in the list.

In addition, distinguished keynote speakers who are internationally renowned in the field will be giving presentations at the conference. You will also have a chance to discuss your works with the editors of the most respected journals. The accepted submissions will be clustered around their common topics and areas of interest. The final program - released about three weeks before the congress - will mirror the research agendas of the delegates rather than a pre-conceived list of arbitrary topics.

It is up to each delegate how much to submit or publish. Some authors may publish only an abstract in the proceedings. Others may prefer to publish a full-length manuscript in the journal. Delegates may also attend a conference without submitting or publishing any research. Authors may deliver their work during the conference either as a 15-minute oral presentation, a poster session, a panel, or a workshop.

We encourage submissions of paper for the following types of contributions:
– Oral Presentations
– Posters
– Workshop
– Company Presentation
– Virtual Presentations

The congress official language is ENGLISH. All Abstracts, Final Papers and Presentations must be in English. Its typical composition should be summarily: motivation for the paper, objectives, what was done, how it was done and validated, major results and conclusions. The papers must report original, previously unpublished findings in the field. All papers will be reviewed under the direction of the Scientific Committee.

About ISCDBU
ISCDBU was founded in 2011 Simultaneous in the Barcelona & Tehran and quickly evolved into a truly global scientific society promoting forums for interaction among professionals on a tripartite (academia, government and business) and multi-national basis. Communicate and translate science to policymakers and the public. With the establishment of geographic units in North America, Europe, Asia/Pacific, and Latin America by 2012, to promote ISCDBU and its tripartite governance approach as a global organization and to foster international communication on environmental issues through research and education. The ISCDBU facilitates worldwide outreach to scientists, engineers, and managers and encourages development of additional ISCDBU member groups. The geographic units are represented on the Council, with representation keyed to their relative shares of membership. The ISCDBU Global Executive Director position was created in 2013 to support the development of a strong program of science and activities around the world and to coordinate the programs of the geographic units.

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• Connect with universities and the international community regarding the exchange of information, articles, and publications
• Tasks related to fellowships, faculty members
• Facilities for the preparation of books, publications International
• Identify and invite international experts to assist short-term teaching and research
• Tasks related to applicants short and long term training courses
• The organization and supervision of conferences, seminars and congresses in domestic and foreign universities and transmitting them to the colleges, centers and departments
• Research Festival Held annually
• Coordinating the compilation and translation of books by professors and university students
• Hosting annual meetings comprised of conferences, short courses, platform and poster presentations, interactive forums, group meetings and networking events, and the recognition of professional achievements through merit awards
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• Communicating through peer-reviewed journals, books, newsletters, technical publications, webinars and other digital communications
• Interacting and cooperating with other societies to co-sponsor scientific sessions, workshops and meetings
• Facilitating the incorporation of science into decision-making and policy by communicating science to technical and non-technical stakeholders through standing and ad hoc committees, advisory groups and publications, and through direct outreach activities to policymakers and the public via meetings, presentations and by providing written materials focused on specific issues
• Providing opportunities for students and early career professionals in ISCDBU mission-related areas
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• Broadening disciplinary, geographic and human diversity within ISCDBU
• Promoting personal integrity and the scientific process

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The ISCDBU Logo and Trademark Guidelines are intended to clarify and update the specifications of the International Society of communication and Development between universities, name, acronym, slogan and logo (symbol), and to define the conditions of their use.
The purpose of these rules and guidelines is to assure the integrity of the name of the Society, its acronym, slogan and logo (symbol), and to assure proper use so that they will be recognized and respected worldwide. ISCDBU is the sole owner of the name, acronym, slogan and logo, and their use must be explicitly approved by the ISCDBU Board of Directors or Council, with oversight by the ISCDBU World Council, to assure their validity.

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  ▪ Computer & Information Technology
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  ▪ Electrical and Electronics
  ▪ Engineering and Technology
  ▪ Geography
  ▪ Geology
  ▪ Health and Medicine
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  ▪ Interdisciplinary
- Language and Literature
- Law
- Management and Business
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- Physics
- Psychology
- Sociology and Politics
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- Statistics
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- Agriculture and Animal Science
- Art and architecture
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- Code of Ethics

- Members of the International Society of communication and Development between universities (ISCDBU) are expected to exhibit the highest standards of integrity and professionalism. To ensure a strong and successful organization, our activities require honesty and equity and should reflect well on the Society. In the spirit of promoting Quality Through Science®, members should strive to be good stewards of Development of Science and effective and objective contributors to the discussion globally as well as locally.

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  - Respect the rights, interests, and contributions of professional colleagues.
  - Respect intellectual property and provide appropriate attribution for all intellectual property arising elsewhere.
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  - Not knowingly make false or misleading statements, or engage in activities that could be viewed as defamatory about a professional colleague or an organization.
  - Recognize and respect confidentiality while being honest and forthcoming in all issues of public record.
  - Objectively and clearly communicate scientific methods, understanding and knowledge in a professional manner

- Public Outreach Policy

- ISCDBU Public Outreach Guidelines and Procedures

- Objective:

- To establish an agreed procedure within ISCDBU to review and approve prospective public pronouncements by ISCDBU, its subsidiary groups, or by ISCDBU members proposing to speak on behalf of the Society, doing so in a timely manner and in a way that fully addresses the respective interests and concerns of ISCDBU’s tripartite membership.

- Agreed Principles:

- Public outreach should serve to enhance the standing of ISCDBU science and promote progress toward "Quality through Science."
- Public outreach must draw on tripartite consensus science and debate within the Society.
- Public outreach should focus on relevant scientific issues of interest to the global and local scientific communities and to the public at large.
- Public outreach will generally occur by agreed written communications, although oral presentations may be approved by the ISCDBU World Council when circumstances warrant.
- Internal ISCDBU review and authorization process should be expeditious to the extent possible with final approval by the President of ISCDBU in consultation with a core group of Society leaders, including the Global Executive Director and the chairs of relevant committees (Science Committee, Public Relations and Communications Committee, Publications Advisory Council in the first instance).
ISCDBU Geographic Unit Councils, working committees and the steering committees of Scientific Advisory Groups, with tripartite participation and consensus, may issue public statements on behalf of the GU, working committees after consultation with the ISCDBU World Council President and Global Executive Director, whose roles are to ensure that such statements enhance the standing of ISCDBU science.

Procedures:

The ISCDBU World Council, Geographic Unit Councils or Boards, working committees or the steering committee of a Scientific Advisory Group (SAG) within ISCDBU may identify potential issues and consult within ISCDBU and with the respective Executive Directors (EDs) to make an initial determination of the need and relevance for ISCDBU public statements. ISCDBU EDs are charged with following broader policy developments so as to be able to advise appropriately and to alert the World Council, GU Councils or Boards or approved groups to potential public outreach opportunities of benefit to ISCDBU.

Trademark Policy

ISCDBU Logo and Trademark Policy

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Investigation of dependence of shock reflection phenomena in overexpanded supersonic nozzles on specific heat ratio

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Abstract

The study of supersonic jets is important in many engineering applications. Issuing of the supersonic jet from the nozzle may occur in the overexpanded mode, when the pressure in the gas flow from the nozzle outlet is less than the ambient pressure. In a planar overexpanded nozzle flow two oblique shocks are created that start at the nozzle lips and are directed towards the symmetry plane. These incident shocks can reflect either the regular reflection or the Mach reflection. Triple shock configuration can be calculated independently of a boundary problem using a triple-shock theory. The boundaries between regular and two types of Mach reflection (with a positive reflected angle and a negative one) have been calculated analytically for the determining parameters: Mach number of inflow, ratio of specific heats, jet pressure ratio (ambient pressure/pressure at the nozzle exit). The processes of the exhausting of supersonic jet from flat ideal and tapered nozzles have been investigated numerically for two values of specific heat and different initial parameters.

Keywords: "numerical simulation; mach reflection; triple shock configuration; supersonic nozzles" ;

1. Introduction

The study of supersonic jets is important in many engineering applications. The transition from one type of reflection mode in the jet structure to another is a subject of the research of many scientific groups: Hadjadj A. et al. (2004), Shimshi E. et al. (2011), Hadjadj A. et al. (2015), Martelli E. et al. (2015). However, in spite of the long history of problem a complete understanding of the process does not still exist. In the present paper the process of the exhausting of a supersonic jet from flat ideal and tapered nozzles has been investigated in dependence on the ratio of specific heats.

Some dependencies of shock disposition in triple configurations on specific heats ratio $\gamma$ have been studied recently in the papers of Gvozdeva and Gavrenkov (2010, 2011). New triple configuration with a negative angle of reflection has been found. The effect of the value of $\gamma$ on the regular/Mach reflection (RR/MR) transition criteria has been also found and the regions of double-shock, triple-shock and the new configurations have been constructed as a function of the values of specific heats ratio, flow Mach number and angle of incidence. It has been shown that the appearance of the negative angle configuration in a stationary supersonic gas flow might lead to the choking of the flow (Gvozdeva and Gavrenkov (2015)).

The suggestion has been made in Gvozdeva L.G., Chulyunin A.Yu (2015) that the onset of this configuration in the supersonic jet exhausting from a rocket nozzle might also lead to a negative effect on the performance of the nozzle. Numerical studies of the dependence of the structure of the nozzle flow on the ratio of specific heats have been made in Chulyunin A.Yu, Gvozdeva L.G. (2015). It has been suggested that the onset this configuration in the problem of jet discharge may result in the formation of a closed area in which the vortex flow develops behind Mach wave. Figure 1 shows the proposed scheme. It has been suggested, the gas begins starts to accumulate in the closed area behind Mach stem, and it starts to move towards the exit of the nozzle that can lead to devastating consequences - to the disruption of the stable operation of a rocket engine. Scheme of the appearance of the triple configuration with a negative angle of reflection is given in Figure 2

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If we consider the three-shock configuration without any reflective surfaces, the location of the configuration of the waves depends on three parameters: the angle of incidence $\omega_1$, the Mach number of the incident flow $M_1$ and the ratio of specific heats $\gamma$. Figure 2 shows that with a decreasing $\gamma$ the angle of the reflected wave increases and after the limit position $\omega_1=\omega_g$ ($\omega_2=0$) the reflected wave begins to lie in the same plane as the Mach wave. It has been shown in Gvozdeva L., Gavrenkov S. (2015) that the effect of the appearance of such abnormal configurations in the boundary value problem of flow around a system of two wedges (model of an air intake) leads to an unstable motion. In the present paper we will investigate the influence of the ratio of specific heats on the outflow of gas from the nozzle in the overexpansion mode. In this case, the determining factors will be: Mach number $M_1$, ratio of specific heats $\gamma$ and pressure ratio in the incident wave $P_2/P_1$. First of all, the analyzed the triple configuration for these defining parameters has been carried out.

2. Analytical studies of a triple-shock configuration

To describe the jet flow, boundaries of the existence of reflection boundaries in determining the coordinates $P_2/P_1$, $M_1$ and $\gamma$ must be obtained. The results of these calculations are shown in Figure 3-5. Figure 3 given the boundary of the configuration with a negative angle of reflection $\omega_2=0$ for different values of the ratio of specific heats, a region with a negative angle is within the respective curves. The Figure 3 showed that at $\gamma = 1.4$ region with a negative angle does not exist, there is only a regular Mach reflection. The boundaries between regular and Mach reflections for $\gamma=1.4$ are well known (see Shimshi E. et al.(2011)). The results are shown in Figure 4. The region above the line $AB$ corresponds to Mach reflection; $ABCD$ region (blue) contains Mach and regular reflection. The region below $DC$ line matches only regular reflection. Figure 5 shows the location of areas of different configurations of shock waves regions for the defining parameters $P_2/P_1$, Mach number at the outlet of the nozzle $M_1$ and $\gamma=1.2$, where there are all kinds of reflection and a new area of double solution. The area $AGHCA$ (blue) contains two different solutions that match the regular reflection and Mach reflection. Area $GEHG$ (yellow) has two solutions: regular and irregular reflection with a negative angle; area below $DC$ provides a single solution with a regular reflection; an area that lies above $AGE$ contains only Mach reflection.
3. Numerical simulation of the structure of the jet flowing out of the tapered nozzle

On the basis of numerical simulations the process the expiration of a supersonic jet from a flat tapered nozzle with two values of specific heats and different NPR parameters has been investigated. This parameter is the ratio of the pressure at the nozzle inlet to the pressure in the environment. As the object of study a tapered supersonic nozzle is considered. The geometric parameters are: Throat width, $D_t - 16$ mm; area ratio of the exit section of nozzle to the throat, $A_e/A_t - 4$; angle of the nozzle – $10^\circ$; length of the computational domain, $L_d - 2400$ mm; height of the computational domain, $H_d - 1600$ mm; radius of curvature of the convergent part, $r_c - 24$ mm . The computational domain is chosen from the condition that the distance from the nozzle exit to the exit boundary equals to not less than 10 diameters of the output section. The resulting geometrical model is imported into the software package STAR-CCM+, in which the mesh model was established and further calculations were carried out. To split the geometry on the finite volumes the unstructured polyhedral mesh has been used with smoothing at the solid walls (Peric M.(2004)). The advantages of polyhedral cell type over tetra or even to structured hexagonal cells are described in detail. Note that the polyhedral cells for the same amount of elements to allow describe the gradients better than tetra and structured hexa-cells. This is particularly important in the study of supersonic gas flow, which often has to deal with large gradients (shock waves, rarefaction wave, etc.). It should also be noted that the use of polyhedral cells reduces the time for the calculations due to the more rapid achievement of the convergence.
The turbulent flow is modeled in the present study. In the numerical study of turbulent flows it is important to create on the surface of wall not only small but also quite uniform grid with a little stretching in height. This is called the creating the prismatic layer of cells. The size of the first layer is selected basing on the used turbulence model. In this case, a model SST was chosen and \( y' \) for this model should not exceed 5.

A system of Navier-Stokes equations, Reynolds averaged, and the energy equation used to describe the dynamics of a viscous turbulent gas flow in the nozzle. This system has the following form (Belov I.A., Isaev S.A. (2001)):

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \\
\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_j u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j u_i}{\partial x_j} \right] \\
\frac{\partial \rho c_p T}{\partial t} + \frac{\partial \rho u_i c_p T}{\partial x_j} = \frac{\partial q_i}{\partial x_j} + \frac{\partial \tau_{ij} u_i}{\partial x_j}
\]

Where \( \rho \) - density, \( T \) – temperature, \( u_i \) - the i-th component of the velocity, \( i = 1,2,3 \), \( x_i \) - coordinates, \( C_p \) - specific heat at constant pressure, \( \tau_{ij} \) - viscous stress tensor, \( q_i \) - heat flux due to the thermal conductivity \( \lambda \). Expression \( (\rho u_i u_j) \) is called the Reynolds stress tensor, which is used to close the turbulence model SST, the equation for which are given by Belov I.A., Isaev S.A. (2001):

\[
\frac{\partial \rho k}{\partial t} + u_j \frac{\partial \rho k}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho k \omega + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \\
\frac{\partial \rho \omega}{\partial t} + u_j \frac{\partial \rho \omega}{\partial x_j} = -\gamma k \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[ (\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_t) \frac{\rho}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}
\]

Where \( k \) - kinetic energy of turbulent fluctuations, \( \omega \) - specific energy dissipation rate, \( \beta, \beta^*, \sigma_k, \sigma_\omega \) – turbulence constants. Turbulent viscosity and Reynolds stresses are determined similarly as in the \( k-\omega \) model, namely:

\[
\mu_t = \frac{\rho k}{\omega} \\
\tau_{ij} = -\rho u_i u_j
\]

Equations (1) - (7), together with the boundary conditions form a closed system which can be solved by numerical methods.

Figures 6 (a-c) show the calculated jet with \( \gamma = 1.4 \). At \( NPR = 20 \) (not shown) this structure is characterised of regular reflection. The point of intersection of two incident shocks is disposed at a certain distance from the outlet of the nozzle. \( NPR \) is reducing to 10 the structure is resembled the regular reflection, however, the point of intersection moves inside the nozzle, because there is a small flow separation. With further decrease of \( NPR \) to 5, the numbers of "cells" inside the nozzle increase. The subsonic region behind Mach waves appears. As \( NPR \) reduces, the subsonic region is close to the point of reflection. The separation zone is greatly increased. This mode is preceded the formation of Mach reflection. Note that usually in ideal nozzles Mach reflection should appear after regular reflection before the flow separation. The observed inverse sequence is typical for the tapered nozzles (Shimshi E. et al.(2011)).

Figure 7, 8 show the results of the calculation of the jet with \( \gamma = 1.2 \). Note that for the same \( NPR \), compared to \( \gamma = 1.4 \), the reflection point is closer to the nozzle exit as in the case with \( \gamma = 1.4 \). In addition, the flow separation on the same modes is substantially less.
4. Numerical simulation of jet expiration from flat Ideal Nozzle

The results presented above describe a complex system consisting of a flow in the inner part of the nozzle and the jet expiration process. However for the aim to obtain a configuration with negative reflection angle only a process of expiration with constant $M_1$ should be investigate. For these cases, a model has been created, which is a rectangle of dimensions 4x2 m. Thickening is done at the site of the jet exit. The simulation in a progress, the first results are shown. Calculations were carried out with $\gamma=1.2$ and $M = 3.67$. Jet pressure ratio (JPR) is variable. Figure 9 (a,b) presents the field of Mach numbers at various JPR.
NPR = 5 and 8, respectively. As can be seen Figure 9a corresponding to the lower value of JPR regular reflection occurs, Figure 9b - Mach reflection.

5. Conclusion

The boundaries between regular and two types of Mach reflection (with positive reflected angle and a negative one) had been calculated analytically for the determining parameters: Mach number of inflow, the ratio of specific heats, jet pressure ratio (ambient pressure/pressure at nozzle exit). The processes of the exhausting of supersonic jet from flat ideal and tapered nozzles have been investigate numerically for two values of specific heat and different initial parameters. The calculations have been made numerically for the flat tapered nozzle for the values of specific heats γ=1.4 and 1.2 the value of the parameter NPR being 20, 15, 10, 5. With the parameter NPR = 20 there is a typical structure for regular reflection with the intersection point at the axis located near the exit of nozzle. When reducing NPR to 10 the structure resembling the regular reflection remains, however it is shifted into the nozzle, the flow separation occurs. With further decrease of NPR to 5 the number of consecutive normal shock waves in the nozzle increases. Subsonic zones behind Mach waves appear. This mode is preceded to the formation of Mach reflection. For the same value of the parameter NPR, but at a smaller value of γ, the intersection point shifts further away from the inlet section of the nozzle. The flow separation becomes substantially less. Investigations for an ideal nozzle have been made with the aim to study the appearance of configuration with negative reflection angle in a jet flow. The first results are given.

Acknowledgements

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Analysis of the rational use of the elastic properties of the system of ropes and blocks for modeling the electric main lift bridge foundry crane with two drive motors


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Abstract

This scientific article considers the idea of the mechanical part of the main lift twin-engine electric overhead casting crane and construction of its logarithmic amplitude-frequency characteristics to determine the appropriateness of accounting elastic ties in the mathematical model of the drive with the help of some estimate parameters of the logarithmic amplitude-frequency characteristic (LAFC). It presents a structural scheme and mathematical model of mechanical part of electric drive for the three main states of movement: normal operation, the rise and descent of the load at failure of one engine. Modeling and calculation of the logarithmic amplitude-frequency characteristics of the system implemented in MATLAB (Simulink package). Generalized parameters have been calculated that allow analyzing the logarithmic amplitude-frequency characteristics response and giving a rationale for consideration of elastic ties in the drive operation simulation.

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Keywords: casting crane; main hoist unit; dual-motor drive; mathematical model of the mechanical components; elastic coupling; simulation; log-magnitude and phase diagram.

1. Introduction

Crane facilities play an important part in the material handling. They provide supply with row materials and semi-finished products, transport of finished products and assist at mounting and repair of various equipments. Cranes are very essential units, their operation influences the yield of the whole process line.

All cranes are operated according to the set or non-predetermined cycle. Any lifting mechanisms are operated in the steady-state mode most of the time. At this, the period of transient processes is relatively short.

It should be noted that dynamic torques in transient modes result in a significant load of such kinematic assemblies as gear units, shafts, ropes, etc. Such elements as ropes are characterized by elasticity. Here, backlashes are also characteristic for power transmissions. Crane mechanisms with the electric drive shall be considered as a unified electromechanical complex. The multi-mass mechanical portion with elastic couplings and electric portion of these systems are in continuous interaction in dynamic modes. Control and disturbance actions in this system leads to transient processes accompanied by energy exchange between its elements. Similar events result in load swinging, vibrations and additional loads on kinematic assemblies, which deteriorates installation accuracy and quality of all operations. When positioning load, its swinging due to transient modes results in a "parasite" increase of the process cycle period [1]. If applicable, dynamic processes at simulation of electromechanical systems shall be investigated with the most accurate mathematical model of the mechanical portion of the electric drive. Unfortunately, even an accurate mathematical model considering elastic couplings cannot significantly provide accuracy and reliability of the simulation outcome. In some cases, the may reduce the calculation speed at system simulation. Furthermore, considering elastic characteristic and gaps in transmissions is unnecessary in some practical cases as they do not have any impact on operation of the whole electric drive.

2. Problem statement

This paper will examine the rationale for inclusion of the rope rigidity into a mathematical model. Furthermore, it will estimate the possibility to represent the unit as a rigid link, i.e. as a single-mass system. For this purpose, a mechanical portion should be represent as a controlled object. Then, the unit's log-magnitude and phase diagram is to be plotted, some estimation parameters should be determined and briefly analyzed. That is the mechanical portion of the electric drive that is of the greatest interest in the context of plotting the magnitude curve. The mathematical model considers elastic couplings between the cable reels and the beam. When simulating and computing, double-increase of the inertia of rotating parts during load descent in the emergency mode shall be taken into account. This event can be explained by the use of the ratchets in the gear units.
3. Main part

Estimation of the mechanical portion behavior is required to determine the practicability of considering elastic couplings at simulation and operation of the electric drive. To enable coupling analysis, a mechanical portion should be represented as a controlled object. A diagram of the mechanical portion of the dual-motor drive of the main hoist of the casting crane equipped with ratchets in the gear units has not been yet regarded. The overview literature pays attention to theoretical information on typical one-motor hoists only. The most investigation portion is devoted to mill-type ladle cranes related to the issues of mechanics and heavy engineering. Thus, [1] provides a general theoretical information on representation of the mechanical portion of the single-drum rope hoist as a double-mass system and general guidelines for calculation and analysis of amplitude-frequency characteristic. [2] gives a relatively deep insight into the issues of control of crane electromechanical systems. It determines some structural configurations of the mechanical portion of the electric drive. It also describes various magnitude characteristics and peculiarities of the unit operation. [3] provides very essential data on possible representation of the pulley lift system as a diagram with one rope, which rigidity is equal to the full pulley lift's one.

The paper considers an actual mechanical portion of the main hoist of the overhead casting crane No. 3 operated at the arc-furnace plant of Ural Steel JSC. The crane is mounted in the plant charging bay and intended for charging scrap metals into the arc steel furnace. Specifications of the main hoist of the casting crane are provided in [4]; its kinematic diagram is shown in Fig. 1.

The main hoist consists of two similar, symmetrically arranged single-drum hoist drives. Each of two hoist mechanisms is composed of an electric motor, two mechanical brakes, a double-reduction gear unit, an open gear set and a drum. Rims of two drums are constantly coupled. It provides their constant rotation rates and synchronism of the load lift. Drives are designed assuming possible operation with only one drive. It helps to complete an operation in the case of failure of one of the drives.

Two ends of two double blocks are attached to every load drum. The lower movable hoisting blocks are installed on the welded lifting beam, to which lamellar hooks are attached. When lifting loads, it is highly important to provide a greater reliability of the hoist mechanism. It is achievable due to the use of two motors and two brakes for each motor. Each drive has a ratchet wheel built-in into the gear unit. It helps to complete an operation in the case of failure of one of the drives. The ratchet device is operated as follows: the collar with pallets is attached to the output gear shaft. The ratchet gear wheel freely rotates at the collar boss assembly. Under normal operation conditions, the pallets are supported in the ratchet socket and engage the gear wheel. No power contact between the drum gear wheels is present in this case. Any failures during load lift result in a power contact between the drum gear wheels and lead to pallets' slipping along the ratchet sockets of the lag ratchet gear wheel. In this case, the second motor takes the full load and rotates both drums [5].
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Under emergency conditions, the load is distributed as follows: under influence of the load mass, the ratchet pallets are safely supported by the ratchet sockets. Changing rotation direction of the electric motor during descent results in turn of the ratchet gear wheel from the side of the operated motor in direction of the ratchet rotation. Load mass substantiates a constant ratchet pallet support at the side of the operated motor. The gear wheel and ratchet rotate co-directionally. Contemporary, a power contact between the drums causes the turn of the second drum to the side of load descent. The engaged gear of the drum-pinion unclosed pair is responsible for rotation of the ratchet neighboring on the shaft, which teeth are engaged in the sockets of the second gear wheel at the side of the failed electric motor. As a result, rotational components taking part at load descent will include complementary to the motor shaft, gear unit, pinion, ratchet, gear unit and shaft of the second electric motor, which will result in duplication of inertia.

Under normal operation conditions, when both motors are functional and loads are accurately distributed between both motors, the gears between the drums are not loaded. The torque is transmitted at the failure of a drive only. In connection with the above, the design diagram has no mechanical link between the drums. As we can see, the system is three-mass under normal operation conditions. The first and second mass is formed by rotating parts: the drive motor, gear unit, unclosed pair and cable reel. Their inertia will be $J_1 = J_2 = 50.4 \text{ kg m}^2$. The third reciprocating mass is generated by the moving beam with the nominal load and ten pulley lift rolls, which inertia $J_3 = 1.579 \text{ kg m}^2$.

When developing the structural configurations, the pulley lift is replaced with the provided configuration with one rope, which rigidity is equal to that of the pulley lift [3].

$$C_{12,1} = C_{12,2} = \frac{E_K \cdot F_K \cdot m \cdot a \cdot p^2}{L} = \frac{1.4 \cdot 10^5 \cdot 10^6 \cdot 0.075 \cdot 2 \cdot 0.00251^2}{30} = 26460 \text{ Nm},$$
where $12_{1.2}$ – equivalent rigidity between the first and second mass corresponding to the first and second winches; $E = 1.4 \times 10^5$ MPa – elasticity modulus of the rope with a metal core to be applied according to [6]; $F$ – rope cross section area, m$^2$; $m$ – pulley lift rate; $α$ – pulley lift number; $ρ$ – reduction radius, m/rad; $L$ – lift height, m.

The reduced pulley lift configuration is shown in Fig. 2. The above enables representation of the design diagram (Fig. 3) as a structural configuration of the mechanical portion shown in Fig. 4.

Under emergency conditions, the kinematic chine is opened at the side of the failed motor. The latter and a part of gear unit are switched off at lifting. The inertia of the drum, gear wheels of the unclosed pair and ratchet in the gear unit is added to the first mass. However, their own inertia practically does not affect on the total value of the rotating component inertia due to low own inertias and a high gear ratio of the unit. It is doubled at descent as a power contact between the drums at their rotation in the descent direction enables rotation of the second winch up to the electric motor.

In this case, the design diagram will have the variant shown in Fig. 5.

![Fig. 2. Reduced pulley lift configuration](image)

![Fig. 3. Design diagram of the mechanical portion under normal operation conditions](image)

$J_1$ – inertia of the first mass (of the drum and gear unit of the first winch); $J_2$ – inertia of the second mass (of the drum and gear unit of the second winch); $J_3$ – load inertia; $ω_1$ – resulting rate of the first mass; $ω_2$ – resulting rate of the second mass; $ω_3$ – generalized rate of the third mass expressed through the travel speed.
by means of the reduction radius; \(M_{13}\) and \(M_{23}\) – torques of tensile correlation between travelling masses of the system

Fig. 4. Structural configuration of the main hoist of casting crane for normal operation conditions

As we can see, the mechanical portion is represented as a dual-mass system under emergency conditions. Here, the equivalent rigidity of the pulley lift system shall be calculated with the same formula, the only difference being duplication of the hoisting blocks; thus, \(J_{1\text{ em}} = 52,921 \text{ Nm}\). Obviously, \(J_{1\text{ em} = J_1}\); at descent, \(J_{1\text{ em} = 2J_1}\). With due regard to the above, let us represent the design diagram in Fig. 5 as a structural configuration of the mechanical portion shown in Fig. 6.

To enable a further analysis of the mechanical portion under emergency conditions, it is rationally to determine some generalized parameters [2, 7, 8]. The correlation of the inertias for load lift and descent in the emergency mode is as follows:

For normal conditions (provided, \(J_{12} = \frac{J_2}{12}\)):

\[
\Omega_{12\_lift} = \Omega_{12\_descent} = \sqrt{\left(2C_{12\_l}\right) \frac{J_1 + J_3}{J_1 \cdot J_3}} = \sqrt{\left(2 \cdot 26460\right) \frac{50.4 + 1.579}{50.4 \cdot 1.579}} = 185.9 \text{ 1/s}.
\]

For emergency conditions:

\[
\Omega_{12\_lift} = \sqrt{C_{12} \frac{J_1 + J_3}{J_1 \cdot J_3}} = \sqrt{52921 \frac{50.4 + 1.579}{50.4 \cdot 1.579}} = 186.0 \text{ 1/s},
\]

\[
\Omega_{12\_descent} = \sqrt{C_{12} \frac{(J_1 + J_2) + J_3}{(J_1 + J_2) \cdot J_3}} = \sqrt{52921 \frac{50.4 + 50.4 + 1.579}{(50.4 + 50.4) \cdot 1.579}} = 184.5 \text{ 1/s}.
\]

The resonance frequencies relative to the load inertia for lift and descent:
Based on the initial and calculated parameters and structural configuration in Fig. 4 and 6, let us make up a mathematical model of the mechanical portion. The log-magnitude and phase diagram is generated with the Control Analisys tool of the MATLAB’s Simulink package. All log-magnitude and phase diagrams are located on one graph shown in Fig. 7. The obtained magnitude characteristics are used for analysis of main properties of the drive mechanical portion.

The log-magnitude and phase diagram has a slope of -20 dB/decade within the low-frequency region; discontinuity takes place at the resonance frequency only and tends to the asymptote with a slope of -40 dB/decade in the high-frequency region. An increase of the mass relation causes a small LAFC shift down along the amplitude axle and, thus, change of the system break frequency. Generally, the unit LAFC practically does not depend on conditions of the mechanical portion.

The motion of the first mass at low frequencies of the control action fluctuations is defined by the total inertia of the electric drive; at this, the mechanical portion behaves as an integrating factor. At \( M = \text{const} \), the rate is changed according to the linear law superimposed by fluctuations due to the elastic coupling. When the fluctuation frequency is approximate to the resonance fluctuation amplitude, the rates are increased and tend to infinity. However, resonance manifestations greatly depend on parameters of the mechanical portion. Firstly, if the load inertia is far less than the first mass \( (J_3 < J_1, \gamma \to 1) \), the motion of the first mass is near to that determined by the integrating factor. Secondly, the motion of the first mass is determined by the same integrating factor at \( \Omega \to \infty \) in the low and medium frequency region.

3. Conclusion

Investigation of dynamic processes in the mechanical portion of the electric drive of the complex crane facilities, considering specific parameters (gaps, elasticities, etc.), provision of rationale for their consideration and combined action of the improved drive mechanical portion and control system (over the longer term) are highly relevant objectives; this issue has been still insufficiently explored. Thus, this paper being an initial investigation stage has generated mathematical models of double-mass ED mechanical portion in different modes, LAFCs for various unit conditions and analysis of the generalized parameters of the double-mass mechanical systems and revealed impracticality of considering elasticities in the system as they will not have any serious impact on the operation of the investigated crane electromechanical system.
References

A software to optimize the design of ventilated rainscreens

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Abstract

Ventilated rainscreens are one of the most effective solutions for the realization of the opaque parts of buildings, subjected to particularly high environmental stress: rain water pushed by the wind, warming effect of sunshine, frost. They fully enable the outer shield to separate from the building core, thereby allowing, inter alia, also to realize dark color of skins, up to absolute black, unrealizable with ETICS, unless we accept the high risk of serious pathologies. Ventilated rainscreens have been studied since the 70’s by Research Organizations like CSTB’s Groupe Spécialisé n. 7, and now are currently used, designing them in an intuitive and synthetic manner, on the basis of the relevant literature. Up to this time it wasn’t a calculation algorithm that would allow to optimize their design; fills this gap a specific calculation software, developed by the authors as part of the research activities of La.Te.C. - Laboratory of Building Technology, active in the School of Engineering of the University of Basilicata - Potenza.

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Keywords: ventilated rainscreen, aeraulic behaviour, computer aided design

1. Introduction

Ventilated rainscreens are one of the most effective solution for the realization of the opaque parts of buildings, subjected to particularly high environmental stress: rain water pushed by the wind, warming effect of sunshine, frost. They enable fully to separate the outer shield from the building core, thereby allowing, inter alia, also to realize dark color of skins, up to absolute black, unrealizable with ETICS, unless we accept the high risk of serious pathologies.

Nomenclature

\begin{tabular}{|l|l|}
\hline
A_{defl}/A_1 & Intake Area [m\textsuperscript{2}]; \\
A_2 & Output Area [m\textsuperscript{2}]; \\
A_{a} & Part of solar radiation absorbed [-]; \\
\alpha_0 & Convective heat transfer coefficient between the outside panel and the air [W/m\textsuperscript{2}K]; \\
\alpha_{c1} & Convective heat transfer coefficient between the outside panel and the cavity [W/m\textsuperscript{2}K]; \\
\alpha_{c2} & Convective heat transfer coefficient between the cavity and the insulation [W/m\textsuperscript{2}K]; \\
\alpha_{db34} & Heat transfer coefficient (conduction, radiation and convection) of insulation [W/m\textsuperscript{2}K]; \\
\alpha_{db45} & Heat transfer coefficient (conduction, radiation and convection) of base layer [W/m\textsuperscript{2}K]; \\
\alpha_{in} & Convective heat transfer coefficient between the base layer and the room [W/m\textsuperscript{2}K]; \\
\alpha_r & Radiant heat transfer coefficient between the outside panel and the insulation [W/m\textsuperscript{2}K]; \\
q_{sun} & Solar radiation [W/m\textsuperscript{2}]; \\
C_a & Specific heat of the cavity air [J/KgK]; \\
C_1 & Specific heat of the given exterior panel/layer of the façade [J/KgK]; \\
C_3 & Specific heat of the insulation [J/KgK]; \\
C_p & Pressure coefficient for walls (it is 0,6 for windward side, it is -0,3 for downwind side); \\
C_{p2} & Pressure coefficient for roof (it is -0,3); \\
C_{ij} & Admittance coefficient [-]; \\
d_{cavity} & Cavity thickness [m]; \\
d_{1} & Thickness of the given exterior panel/layer of the façade [m]; \\
d_{2} & Thickness of the insulation [m]; \\
\Delta P_s & Pressure difference relating to stack effect [N/m\textsuperscript{2} or Pa]; \\
\Delta P_{wind} & Pressure difference relating to wind effect [N/m\textsuperscript{2} or Pa]; \\
g & Acceleration due to gravity force [9,81 m/s\textsuperscript{2}]; \\
h & Height of observation [m]; \\
h_0 & Height of neutral pressure level [m]; \\
H & Height of interest for recording wind velocity [m]; \\
H_{met} & Anemometer’s height on ground level [m]; \\
\hline
\end{tabular}
$\theta_0$ Temperature of external air [°C];
$\theta_{1,1}$ Temperature of the exterior face of the given exterior panel/layer [°C];
$\theta_{1,2}$ Temperature of the interior face of the given exterior panel/layer [°C];
$\theta_2$ Temperature of the air in the middle of the cavity [°C];
$\theta_3$ Temperature of the external face of insulation layer [°C];
$\theta_4$ Temperature of the internal face of insulation layer [°C];
$\theta_5$ Temperature of the internal face of base layer [°C];
$\theta_{room}$ Temperature of room [°C];
$\theta_{cavity}$ Entry air temperature [°C];
$q_{sun}$ Solar radiation [W/m$^2$];
$q_{cavity}$ Airflow in the cavity [m$^3$/s];
$q_{stack}$ Airflow generated from stack effect [m$^3$/s];
$q_{v,turb}$ Airflow generated by wind turbulence [m$^3$/s];
$\rho_a$ Density of cavity air [Kg/m$^3$];
$\rho_1$ Density of the given exterior panel/layer [Kg/m$^3$];
$\rho_i$ Density of the insulation [Kg/m$^3$];
$\rho_{out}$ Density of the external air [Kg/m$^3$];
$T_{in}$ Absolute inside temperature [°K];
$T_{out}$ Absolute outside temperature [°K];
$V_{win}$ Wind velocity [m/s];
$V_1$ Air velocity in $A_1$ [m/s];
$V_2$ Air velocity in $A_2$ [m/s];
$V_e$ Wind velocity [m/s];
$V_{e,h}$ Wind velocity on the building wall at the height of interest [m/s];
$V_{e,met}$ Wind velocity as recorded by meteorological station [m/s];
$z_1$ Parameters relating to the type of site;
$z_2$ Distance between the center of intake area and height of neutral pressure level [m];
$z_3$ Distance between the center of output air area and height of neutral pressure level [m];

Ventilated rainscreens have been studied since the 70's by Research Organizations like CSTB’s Groupe Spécialisé n. 7 (Fleury & Abraham, 1982), and are now currently used, designing them in an intuitive and synthetic manner, on the basis of the relevant literature (Lembo, 1990). Up to this time it wasn’t a calculation algorithm that would allow to optimize their design, responding analytically (both in the case of continuous screens, and in that the elements’ contour of the screen has open joints) to a series of questions, of capital importance for their economic optimization: what is the optimum/minimum thickness of the ventilated cavity? It is correct the statement (formulated by the above mentioned CSTB’s Groupe Spécialisé n. 7) that it must have a maximum height of 23.50 m, beyond which it must be interrupted with a horizontal subdivision, and then present it again above it? Is it necessary the vertical partitioning of the single-sided façade (when the system does not provide it already in any modulus, for its own constitutive mode), so as to avoid that, under the wind pressure, the air flow in the cavity go horizontally, instead of vertically? The continuous screens are more efficient than those with open joints, or is it true the reverse? The presence of horizontal internal structural elements, which reduce the passage section of the air flow, makes the flow turbulent? And if that happens, under what conditions relating to the battens’ interaxis and the thickness of the passage section of the air flow? The color of the outer coating influences the aeraulic behavior of the ventilated rainscreen? The reflective quality of the surface layer of insulation, which receives the radiation produced by the heating of the outer shield, is it important? (i.e., the usual black kraft paper sheet is fine, or, to coat the heat insulating, it would be better to employ a perforated aluminum sheet?)

To all these questions, and many others, a specific calculation software, developed by the Authors as part of the research activities of La.Te.C. - Laboratory of Building Technology, active in the School of Engineering of the University of Basilicata - Potenza (Italy), provides analytical answers.

In the common understanding of those who read it must be assumed that a ventilated rainscreen consists of: 1) a basic structural layer, which supports it and provides it (if desired) the useful thermal inertia requested, performs security tasks to the mechanical and thermal loads belonging its use, can perform an important role for sound insulation to air noise from outside or from the upper and lower levels, is located on its thickness and distributes internal installations and so it is necessary for them, and realizes the interior finishes; 2) a layer of thermal insulation, made with one or more materials of adequate characteristics for the intended use, to the dimensional characteristics of the building and to the thermo-hygrometric and acoustic performance desired; 3) a ventilation layer which, as is known from the relevant literature, must comply with the minimum requirements of the intake air area, of the current airflow area and of the output area, so that the stack effect can be activated, and the rainscreen can be effectively defined "ventilated"; 4) a support layer, that is a skeleton, normally made of wood or aluminum, which holds
the external screen and is supported by the structural base layer by means of metallic shelves (made in stainless steel, common carpentry steel or galvanized steel, or aluminium) that cross the layer of thermal insulation and thus constitute, or may constitute, punctiform thermal bridges; 5.) and, finally, by the outer coating layer, which forms the protective shield around the envelope, more or less continuous and therefore also more or less impermeable to air and water from rain and more or less efficient for the airborne sound insulation. The simulation hypothesis is that behind the ventilated rainscreen there is a room of 4.00 x 4.00 m, 3.00 m tall.

2. Physical-mathematical modeling of a ventilated rainscreen functioning

The model developed for ventilated rainscreens is directly derived from the one previously studied by the authors to model, simulate and analyze the behavior of the DSF - Double Skin Façades (Lembo, Marino & Lacava, 2007 and 2009) and to optimize their design. It is based on the use of MATLAB® Simulink software platform, and is organized on interaction between three subsystems:

- the **thermal** model (see Fig. 1a);
- the **airflow** model (see Fig. 1b);
- the **wind velocity** model (see Fig. 2).

2.1. The thermal model

The **thermal model** simulates the thermal exchanges that occur between the different elements of the ventilated rainscreen, by conduction, convection and radiation, under the action of temperature differences (see Fig.3). The required inputs are the external climatic conditions, the coefficients of heat transfer and air flow, resulting from the **airflow** model.

---

Fig. 1. (a) Thermal model: (1) thermal subsystem, (2) airflow subsystem; (b) Airflow model: (3) wind generator, (4) wind pressure, (5) stack effect
The outputs are the temperatures of all the layers that make up the wall and the internal ambient and the speed of the air flow in the cavity. In every node acts a dynamic system which can be described in non-stationary conditions resorting to differential equation’s solution (from 1 to 5).

\[
\frac{dT_1}{dt} = \frac{\alpha_d (\theta_0 - \theta_{1.1}) + \alpha_c (\theta_3 - \theta_{1.1}) + \alpha_r (\theta_3 - \theta_{1.1}) + \lambda_q - q_{sur}}{(C_1 p_1 d_1 + C_a p_a d_a)^{0.5}} \quad (1) \text{ for } T_1
\]

\[
\frac{dT_r}{dt} = \frac{\alpha_c (\theta_1 - \theta_2) + \alpha_c (\theta_3 - \theta_2) + \rho_a C_a q_{cavity} (\theta_{cavity} - \theta_2)}{C_a p_a d_{cavity}} \quad (2) \text{ for } T_r
\]

\[
\frac{dT_3}{dt} = \frac{\alpha_r (\theta_1 - \theta_3) + \alpha_r (\theta_4 - \theta_3) + \rho_a d_{cavity} (\theta_{cavity} - \theta_3)}{(C_1 p_1 d_1 + C_3 p_3 d_3)^{0.5}} \quad (3) \text{ for } T_3
\]

\[
\frac{dT_4}{dt} = \frac{\alpha_m (\theta_4 - \theta_5) + \alpha_m (\theta_{in} - \theta_5)}{(C_4 p_4 d_4)^{0.5}} \quad (4) \text{ for } T_4
\]

\[
\frac{dT_5}{dt} = \frac{q_{stack}}{q_{stack} + q_{turb}} \cdot q_{turb} \cdot \theta_0 \quad (5) \text{ for } T_5
\]

The air inlet temperature in the cavity is evaluated with the following formula (6):

\[
\theta_{cavity} = \frac{q_{stack}}{q_{stack} + q_{turb}} \cdot q_{turb} \cdot \theta_0 \quad (6)
\]

For the windward side, the turbulent flow is (7):

\[
q_{turb} = 0.05 \cdot A_{defl} + 0.0035 \cdot v_{Win} \cdot A_{defl} \quad (7)
\]

For the side not exposed to the wind, the turbulent flow is (8):

\[
q_{turb} = 0.05 \cdot A_{defl} + 0.009 \cdot v_{Win} \cdot A_{defl} \quad (8)
\]
The heat exchange coefficients, used in the thermal model, were calculated from the general principles of physics and in agreement with the experimental studies by Di Maio & Van Paassen (2001), Stec & Van Paassen (2002), Stec & Van Paassen (2003), Stec (2006) at the University of Technology - T.U. - Delft, The Netherlands.

2.2. The airflow model

The airflow model consists of four sub-systems:
- the stack effect generator, which allows to determine the pressure differences generated by the stack effect or buoyancy, on the basis of the following inputs: external temperature, temperature in the cavity, air density, height of the cavity. The difference in pressure determined by the temperature variation is defined (as in Di Maio & Van Paassen, 2001) by the equation (9): 
\[ \Delta P_s = \frac{\rho_0 \cdot g \cdot (h_0 - h)}{2} \] 

- the wind effect generator allows to determine the pressure difference generated by the effect of the wind on the façade, on the basis of the following inputs: wind speed by the weather station, wind speed measured by the meteorological station in the speed of the wind acting on the surface of the building (13), starting with the following input data: wind speed by the weather station, weather station height, height of the ventilated rainscreen, parameters dependent on the type of ground and the local situation, protected or not (Sherman & Grimsrud, 1980; Burns & Deru, 2003):
\[ v_{w,h} = v_{w,met} \cdot \alpha \cdot \left( \frac{H}{H_{met}} \right)^y \] 

3. Simulations carried out

The software thus developed was applied to two of the most widespread ventilated façades on a global scale, both produced and marketed by StoSE & Co. KGaA in Weizen, Germany:
the model StoVentec R (see Fig.4a) is characterized by the outer coating to organic plaster in opera performed on recycled glass slabs 12 mm thick, with the most various finishes, which may be continuous up to an area of 25 x 25 m (625 m²) without any joint fractionation; the structure consists of a T vertical aluminium, supported by stainless steel shelves;

- the model StoVentec Glass/Stone Massive (see Fig.4b) is realized by hooking large sheets of tempered glass back-colored or natural stone, with or without supporting recycled glass plates of 24 mm thick, equipped on the rear face of hidden attacks, to a horizontal aluminum structure that is held up by the structure of the previously described version; the stone slabs are surrounded by open joints of a few millimeters of width (from 5 to 12 mm).

Fig. 4. (a) StoVentec R (on the left); (b) StoVentec Glass/Stone Massive (in the center and on the right)

The simulations focused on the identification of the evolution, during the whole of the day and night:
1.) the temperature of the different points of the thermal network of the façade;
2.) the pressure inside the ventilation cavity;
3.) the airflow of the ventilation cavity;
4.) the air velocity in the ventilation cavity;
5.) the Reynolds number characteristic of the airflow.

They were made varying, and detecting their impact on the above mentioned parameters, the following variables:
- the color of the finishing material, from white to black;
- the height of the ventilated rainscreen, from 12.00 m to 23.50 m, 30.00 m, 50.00 m;
- the thickness of the air cavity (4 or 8 cm);
- the external wind (absent / present / present with different angles);
- the type of structure (no horizontal rafters / horizontal rafters at intervals of 30 cm or 60 cm);
- the absence / presence of micro ventilation (4 mm) to the contour of the cladding slabs.

Several hundred simulations were run, crossing the different planning solutions. The following figures show the most significant simulations regarding the continuous ventilated rainscreen – StoVentec R (see Figs. 5-8) and the rainscreen with microventilation – StoVentec Glass/Stone Massive (see Figs. 9-11).
Fig. 5. Continuous ventilated rainscreen: ventilation cavity 4 and 8 cm wide, 23.50 m height.

Fig. 6. Continuous ventilated rainscreen: ventilation cavity 4 cm wide; height of 23.50 m, 30 m and 50 m.

Fig. 7. Continuous ventilated rainscreen: ventilation cavity 4 cm wide, 23.50 m height, black and white exterior finish.

Fig. 8. Continuous ventilated rainscreen: ventilation cavity 4 cm wide, 23.50 m height, in the absence and in the presence of wind.
Fig. 9. Rainscreen with microventilation: ventilation cavity 4 and 8 cm wide, 23.50 m height, and step by horizontal rafters 30 and 60 cm.

Fig. 10. Rainscreen with microventilation: wall height 23.50 m, step by horizontal rafters 30 cm, ventilation cavity 4 cm wide, with and without microventilation.
Fig. 11.

Rainscreen with microventilation: wall height 23.50 m, step by horizontal rafters 30 cm, ventilation cavity 4 cm wide, in the absence and in the presence of wind

4. Results and conclusions

The research results and the analyzes conducted on two types of ventilated rainscreen (continuous and with micro-ventilation), have shown that variations in pressure and flow of air within the ventilation cavity are conditioned not only by the height of ventilated rainscreen but also by the thickness, the temperatures, the material and the color of the plaster coating, by the intensity of the wind and its angle of incidence with the ventilated façade, as well as by the presence of horizontal rafters that determine partial obstruction of the ducts ventilation.

In summary, as a result of the countless simulations, it can be stated as follows:

a.) StoVentec R (continuous rainscreen):
the façade with 8 cm ventilation cavity presents turbulent flows thus being less efficient than that by 4 cm; the height of the wall of 23.50 m marks the limit of the transition from laminar to turbulent flow; the color of the finishing and the type of the insulating coating do not affect so significant on the thermo-fluid dynamic variations; the simultaneous presence of the stack and the effect of the wind incidence generates limited turbulent flows, also below the height of 23.50 m.

b.) StoVentec Glass/Stone Massive (rainscreen with microventilation):
the presence of horizontal rafters implies narrowing and widening of the section of the ventilation cavity generating turbulent flows, regardless of the height of the ventilated rainscreen; the turbulence increases, and not decreases, both in the wide section that in that narrow, increasing the thickness of the air duct (it is therefore unnecessary to provide air ducts more than 4 cm); the turbulence decreases if the horizontal rafters are more closely spaced (30 cm instead of 60 cm); micro-ventilation around the elements of the ventilated rainscreen coating determines a greater flow of air flow that in turn generates turbulent flows; the combination of stack effect, wind incidence, and micro-ventilation generates turbulent flows greater than those present in the continuous ventilated rainscreen. It is therefore not true as in general it is stated in commercial publications, that this type of wall is better than a continuous rainscreen, which therefore has advantages not only from the point of view of the air tightness and water proofing and of the isolation to airborne noise, but also in terms of fluid dynamics efficiency.

Contributions

Prof. Filiberto Lembo has coordinated and provided the objectives of the research. Msc. Eng. Francesco Paolo R. Marino has developed methodological and operational tools and verified search results. Msc. Eng. Vincenza Rabasco has done specific analysis in her thesis degree.

The contribution of the authors in editing and writing the text of the paper, was equal.

References

Energy Laboratory.


EMC Analysis of 18-pulse Circuit based on of 3L-NPC AFE Rectifiers with SHEPWM

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Abstract

The article is devoted to electromagnetic compatibility (EMC) analysis of 18-pulse connection circuit based on three level active front-end (3L-AFE) rectifiers with a pulse width modulation selective harmonic elimination (PWMSHE) method. Despite the high number of scientific works in this field, address the problems mentioned in the previous section are unique and it requires the in-depth knowledge of operating principles of 3L converters, multipulse connection schemes and modern PWM methods. The research results show total harmonic distortion (THD) dependencies and harmonic spectrums of grid current and voltage.

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Keywords: "electromagnetic compatibility 18-pulse circuit; AC-DC converter; pulse width modulation; selective harmonic elimination; THD"

1. Introduction

Modern connection methods of powerful industrial consumers of electrical energy to the grid are generally made by three-level (3L) frequency converters with one-directional or bi-directional rectifiers [1-5]. In most cases, high energy performance of bi-directional rectifiers provide electromagnetic compatibility (EMC) and energy efficiency of IEC or IEEE standards for different electrical drives in motor and generative modes [6]. However, deviations from IEC or IEEE standards can arise in operational process of industrial installations that occur as a result of a suboptimal use or choice of a pulse width modulation (PWM) algorithm or/and a frequency switching of semiconductor modules [7-9]. A non-compliance of the EMC standards lead to the following problems:

- Overheating of transformers, reactors and power lines entailing a decrease in their service life and an occurrence emergency situations;
- False responses of high-accuracy protection systems and analog-to-digital instrumentation failures;
- False responses of near or distant power electrical equipment that result from high harmonics in voltage and current power line;
- The penalties from energy companies.

Analysis There is no doubt that any of the foregoing problems can be cause of layup, increasing capital costs and defective products. This observation implies that research and solutions of these problems related to the EMC of powerful electrical consumers are a pending task.

2. "Purpose of Article"

Despite the high number of scientific works in this field, address the problems mentioned in the previous section are unique and it requires the in-depth knowledge of operating principles of 3L converters, multipulse connection schemes and modern PWM methods. Thus, a power circuit of a working reversible electric drive system of a rolling mill has been chosen as a research object and analysis. A main purpose of this article is research of 18-pulse connection scheme, which is based on three 3L natural point clamped (NPC) converters with a selective harmonic elimination (SHE) method for rectifiers.

3. "Research Object"

A plate mill of 5000 hot rolling has been commissioned on OJSC "Magnitogorsk Iron and Steel Works" (MMK) (Fig. 1) in 2009.
This mill power and quality characteristics of the products is the first and one of the few in Russia. Electric drive consist of two synchronous motors (SMs) connecting with work rolls. The SMs are supplied by three 3L neutral point clamped (3L-NPC) BtB converters. The BtB converter consists of 3L-NPC inverter and active front-end (AFE) rectifier. The maximal power of each converter is 8.6 MVA. 18-pulse connection circuit is used for this drive and created by three power transformers connecting in parallel with voltages phase shifts 20°, 0°, and -20°.

Selective harmonic elimination (SHE) or selective harmonic mitigation (SHM) modulation method are often applied to control 3L-NPC AFE rectifiers [10]. In this paper will review only SHE method and present results illustrating the benefits to be gained at the switching minimization for the 18-pulse connection circuit. SHE algorithm allows one to select requisite number of higher harmonics in output voltages of the 3L-NPC AFE rectifier [11]:

\[ n = N - I, \] (1)
where \( N \) is number of the switching angles for a quarter-period, \( n \) is number of the selective harmonics [12].

If the 18-pulse connection circuit is used, only multiple harmonics 18 have a negative effect, consequently, harmonic numbers 18\( n \pm 1 \) should be eliminated. Three switching angles for the quarter-period of the output phase voltages have been selected to minimize the switching. As result, it eliminates the 17th, 19th harmonics and 17th, 19th, 35th, 37th harmonics. The system of equations has been derived to calculate the switching angles for the 18-pulse connection circuit:

\[
\begin{align*}
\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - m &= 0, \\
\cos(17\alpha_1) - \cos(17\alpha_2) + \cos(17\alpha_3) &= 0, \\
\cos(19\alpha_1) - \cos(19\alpha_2) + \cos(19\alpha_3) &= 0 \\
&\vdots
\end{align*}
\]

(2)

\[
\begin{align*}
\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \cos(\alpha_4) + \cos(\alpha_5) - m &= 0, \\
\cos(17\alpha_1) - \cos(17\alpha_2) + \cos(17\alpha_3) - \cos(17\alpha_4) + \cos(17\alpha_5) &= 0, \\
\cos(19\alpha_1) - \cos(19\alpha_2) + \cos(19\alpha_3) - \cos(19\alpha_4) + \cos(19\alpha_5) &= 0, \\
\cos(35\alpha_1) - \cos(35\alpha_2) + \cos(35\alpha_3) - \cos(35\alpha_4) + \cos(35\alpha_5) &= 0, \\
\cos(37\alpha_1) - \cos(37\alpha_2) + \cos(37\alpha_3) - \cos(37\alpha_4) + \cos(37\alpha_5) &= 0.
\end{align*}
\]

(3)

where \( m = \frac{\pi}{\pi \cdot U_{AFE}} \) is modulation index (0 ≤ \( m \) ≤ 1), \( U_{AFE} \) is an amplitude of the 3L-NPC AFE rectifier output phase voltage, \( U_{DC} \) is the rated DC voltage, \( \alpha_1-5 \) are the switching angles.

Solution of the systems (2, 3) has been obtained by using well-known Newton–Raphson method. Among the obtained results, only several variants have been chosen with the following requirements: \( 0 < \alpha_1 < \alpha_2 < \alpha_3 < \pi/2 \). Fig. 3 shows the calculation results of the switching angles and Fig. 4 represents the harmonic spectrum.

![Fig. 3](image-url)
3.5 3.52 3.54 3.56 3.58 3.6 3.62 3.64 3.66 3.68 3.7
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% 500 400 300 200 100 0
\% THD = 2.20%
\% THD = 1.72%

Fig. 4. Grid current at elimination of the 17th, 19th harmonics (a) and the 17th, 19th, 35th, 37th harmonics (b).

4. Conclusion

The electromagnetic compatibility analysis of 18-pulse connection circuit based on three level active front-end rectifiers with a pulse width modulation selective harmonic elimination method has been considered. The research results show satisfactory total harmonic distortion (THD) grid current (2.20% and 1.72%) and harmonic spectrums of grid current and voltage. The research results can be used to assess the EMC powerful three level NPC active rectifiers or inverters.

References

Hydrogen Effect on Duplex Stainless Steels at Very High Strain Rates

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Abstract

Due to their attractive combination of high strength along with great ductility, duplex stainless steels (DSS) are often being used as pressure vessels or underwater pipelines. Another aspect of their use can be reviewed for storing and transporting hydrogen, as a source for renewable energy. The use of DSS alloys in services combined hydrogen and mechanical load can lead to hydrogen embrittlement. The susceptibility to hydrogen embrittlement is directly related to the interaction between traps (microstructural defects) and hydrogen. Hydrogen effects are being studied by a thermal desorption spectrometry (TDS) process. In this research we determine the mechanical properties of DSS alloys with hydrogen at high strain rates (~10\textsuperscript{5} s\textsuperscript{-1}) and compare them to low strain rates (~10\textsuperscript{7} s\textsuperscript{-1}). The first process is being conducted using shock waves by dynamic experiments and the last using quasi-static by tensile loading machine. Dynamic experiments were applied for the first time to DSS alloys with and without hydrogen. The dynamic experiments include dynamic yield stress and spall (rupture) strength. Our results give new insight to the hydrogen embrittlement model regarding high strain rate and high dynamic pressures, ~1 GPa.

In this research we prove that at high strain rates and 1 GPa dynamic pressure, the possible hydrogen failure model is still valid. Calculations performed by TDS showed ~40 % differences in trapping energies of quasi-static and dynamic experiments. Hydrogen trapping in the various defects and its effect on the mechanical properties are discussed in details.

Keywords: Hydrogen; High strain rate; duplex stainless steels; hydrogen embrittlement

1. Introduction

The elastic and plastic properties of hydrogen charged duplex stainless steel (DSS) at high strain rate and high pressure are important for the understanding of their durability at applications combining hydrogen and mechanical load. Measurements of elastic plastic properties at high strain rate in stainless steel alloys can be achieved by dynamic loading \cite{1}–\cite{3}. In this paper we compare between the effect of high strain rate (105 s\textsuperscript{-1}) and low strain rate (10\textsuperscript{-7} s\textsuperscript{-1}) in order to add another milestone to the hydrogen embrittlement failure model \cite{4}, \cite{5}. We study on low strain rates via tensile machine and on high strain rate via plate impact experiments by dynamic loading. In this work, dynamic loading is reported for duplex stainless steel (DSS) which combines austenitic and ferritic (BCC, \(\alpha\)) phases. The effect of hydrogen in DSS under quasi-static loading has been investigated elsewhere \cite{6}–\cite{12}, yet its effect under dynamic loading was not studied and was previously covered by us in 2014 \cite{2}, \cite{13}. Comparison between strain rates at different levels provide insights to the details of hydrogen behaviour at different deformation levels, in order to relate dynamic to static data.

Hydrogen behaviour at different deformation levels was studied by thermal desorption analysis (TDA). The potential failure mechanism and hydrogen diffusion related to it will be discussed in details.

2. Experimental procedure

2.1. Material properties

In this work we used the lean duplex stainless steel (LDS), LDX 2101. The microstructure of LDS consists of equiaxed grains with an average grain size of about 20 \(\mu \text{m}\) as was describes by us in previous studies \cite{14}–\cite{16}. Its chemical composition is \text{Fe}—0.026\%—4.9Mn—21.53Cr—1.53Ni—0.2Mo—0.22N—0.63Si—0.001S—0.025P wt\%. The hydrogen charging condition was gas-phase hydrogen charging at 300 oC and 60 MPa pressure for 3 hr. This charging procedure created an homogenous hydrogen content of 54 wt ppm along the samples’ bulk \cite{14}, \cite{16}. The microstructure of the gas-phase hydrogen charged LDS, published in different works by us \cite{14}–\cite{16}, revealed the appearance of needle shaped sigma (\(\sigma\)) phase with the \text{Fe(CrMo)} composition. This phase plays an important role in the hydrogen embrittlement model.

2.2. Dynamic experiments

Dynamic experiments at strain rate of \(\sim 105\) s\textsuperscript{-1} and dynamic pressure of \(\sim 0.5\) GPa were conducted using 6 m long gas gun. The impact was performed by accelerating an LDS or Al impactor towards an LDS target. The target’s surface is being illuminated by a coherent 532 nm Nd-Yag. The scattered light from the surface is collimated by mirrors and lens and returned to the VISAR \cite{17}, \cite{18}. After impact the targets are softly caught by a special made soft catching cell and are taking to microstructural observation.
2.3. Thermal desorption analysis (TDA)

The characteristics of hydrogen desorption were investigated by means of thermal desorption analysis (TDA). This technique involves accurate measurement of the desorption rate of hydrogen atoms, as solute or trapped in the material, while heating the sample to a non-isothermal heating at a known rate under UHV ~10 µPa. In this work, the samples were heated from room temperature (RT) to 500 °C at constant heating rates of 2 °C/min, 4 °C/min and 6 °C/min. The mass spectrometer was operated under the fast multiple mode detection; the measured intensity channel was set to 2 amu in order to detect hydrogen desorption. The working procedure, as described by Lee and Lee [19] and others [20], allowed for the identification of different types of traps coexisting in the specimen.

3. Results and discussion

3.1. Deformation response

Tensile testing at strain rate of ~10^-7 s^-1 was performed at RT on gas-phase hydrogen charged and non-charged LDS. The results are presented in Table 1. As already showed in previously work of us [16] hydrogen caused an increment in yield strength. This increment was calculated to be 20 % higher in the gas-phase hydrogen charged sample compared with the non-charged sample.

Table 1. Quasi-static experiments results for LDS with and without H.

<table>
<thead>
<tr>
<th>Sample</th>
<th>σ_y ±0.02 [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o H, 10^-7 s^-1</td>
<td>0.32</td>
</tr>
<tr>
<td>with H, 10^-7 s^-1</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Dynamic experiments at strain rate of ~10^5 s^-1, Fig. 1, did not show any change between non-charged and hydrogen charged sample; the dynamic yield strength remained the same. Therefore, it can be said that only when hydrogen has enough time for diffusion, as in the case of lower strain rate experiments, solid solution hardening will occur. This hardening can be related to the pinning of dislocations by the attached solute atoms [4].

![Fig. 1. Experimental measurements of the free surface velocity of LDS with and without hydrogen at dynamic pressures 0.5–1.2 GPa.](image)

The deformation behavior at high strain rate was investigated by calculating the elastic-plastic transition also known as Hugoniot elastic limit (HEL) [1, 34] and rapture (spall) strength from the VISAR profile. The dynamic yield stress under uniaxial strain loading was extracted from HEL, according to the follow relation [22]:

\[
\sigma_{HEL} = \rho_0 C_U HEL
\]

(1)
where \( c_l \) is the longitudinal sound velocity, \( \rho_0 \) is the initial density, \( u_{HEL} \) is the free surface velocity at the precursor front and \( \nu \) is the Poisson’s ratio which was taken as 0.33.

The spall strength, also known as dynamic tensile stress \( \sigma_{spall} \), is proportional to the fracture stress. The \( \sigma_{spall} \) is determined using the measured pull-back velocity \( u \), where \( u = u_{max} - u_{min} \) is the difference between the first maximum (\( u_{max} \)) and the first minimum (\( u_{min} \)) of the target’s free surface velocity. The spall strength is given by the following relationship [22]:

\[
\sigma_{Spall} = \frac{\rho_0 c_0 U (\Delta u + \delta)}{2}
\]

where \( c_0 \) is the bulk sound velocity, \( \rho_0 \) is the initial density and \( \delta \) is the correction for profile distortion.

In all the experiments the presence of hydrogen did not affect the HEL, Fig. 1. These results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dynamic pressure [GPa]</th>
<th>( \sigma_{HEL} \pm 0.05 ) [GPa]</th>
<th>( \sigma_s \pm 0.02 ) [GPa]</th>
<th>( P_{max} \pm 0.20 ) [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o H</td>
<td>1.2</td>
<td>0.75</td>
<td>0.38</td>
<td>0.89</td>
</tr>
<tr>
<td>with H</td>
<td>0.5</td>
<td>0.75</td>
<td>0.38</td>
<td>1.68</td>
</tr>
</tbody>
</table>

Regarding spall strength, calculations predicted a 1.68 GPa spall strength in the hydrogen charged LDS and a 0.89 GPa spall strength in non-charged. Generally, these values are limited since at these dynamic pressures only partial spall was form at LDS. Therefore these calculations give only partial indication on hydrogen effect on spall. In order to better understand these findings the impacted targets were softly caught and collected for metallurgical analysis, Fig. 2. The micrographs in Fig. 2 indicate on two insights: the first relates to spall incomplete, meaning that the cracks did not coalesce into a whole rapture. The second relates to the idea that hydrogen seems to propagate crack motion. This finding clearly presents the hydrogen embrittlement phenomenon and indicates on the same behaviour of hydrogen crack propagation at low and high strain rate (\( 10^{-7} \) s\(^{-1}\) and \( 10^5 \) s\(^{-1}\) at ~0.5 GPa).

Fig. 2. OM analysis of the impacted cross-section targets: (a) non-charged LDS and (b) gas-phase hydrogen charged LDS.

3.2. Hydrogen trapping mechanism

Hydrogen trapping mechanism of gas-phase hydrogen charged LDS samples non-deformed and deformed were studied by means of TDA analysis. The deformed samples include gas-phase hydrogen charged LDS after (10-7 s-1) tensile loading (quasi-static loaded) and gas-phase hydrogen charged LDS after dynamic (105 s-1) loading (dynamic loaded). The desorption peak temperature increases with heating rate, as demonstrated in the TDA spectra, Fig. 3, and the activation energy (\( E_a \)) depends on the critical temperature for desorption (\( T_c \)) and heating rate (\( \varphi \)) [19], [23]:

\[
\frac{\partial \ln \left( \frac{\varphi}{T_c^2} \right)}{\partial \left( \frac{1}{T_c} \right)} = - \frac{E_a}{R}
\]
where R is the gas constant.

By applying Lee and Lee's model [19], the activation energy for hydrogen release may be calculated from the slope of ln(\(\frac{\phi}{Tc^2}\)) versus 1/Tc. According to their model an activation energy value, Ea, equal to or higher than 60 kJ/mol will be ascribed as an irreversible trap, else it will be ascribed as a reversible trap. This notion is highly important since only diffusible hydrogen through lattice sites or hydrogen residing at traps with the lowest activation energy contributes to a metal's embrittlement [24].

In order to evaluate the trap's activation energies, three different heating rates in the range of 2-6 oC/min were applied to the samples. Figs 3 presents TDA spectra of different gas-phase hydrogenated LDS samples non loaded, quasi-static loaded and dynamic loaded; the summary of TDA's results are presented in Table 3.

![Fig. 3. Hydrogen desorption rate as a function of temperature, TDA spectra, of (a) non-loaded, (b) quasi-static loaded and (c) dynamic loaded.](image)

The great differences in activation energies are seen in the quasi-static loaded sample, Fig. 3 b and Table 3. The reason for the great changes between quasi-static loaded and dynamic loaded are due to hydrogen diffusion time and distance which was longer in the quasi-static loaded sample. Diffusion's calculations performed by us in other work [16] predicted 4 times higher diffusion distance for hydrogen in the quasi-static loaded sample compared with dynamic loaded.

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>75-90</td>
<td>20.0±0.5</td>
<td>21-30</td>
<td>19.0±2.0</td>
<td>67-107</td>
<td>20.0±0.5</td>
<td></td>
</tr>
<tr>
<td>143-160</td>
<td>39.0±0.5</td>
<td>117-140</td>
<td>22.0±5.0</td>
<td>122-160</td>
<td>30.0±0.5</td>
<td></td>
</tr>
<tr>
<td>300-340</td>
<td>67.0±2.0</td>
<td>210-300</td>
<td>40.0±0.5</td>
<td>314-353</td>
<td>72.0±2.0</td>
<td></td>
</tr>
</tbody>
</table>

The desorption activation energies were 19.0 ± 0.5 kJ/mol, 22.0 ± 5 kJ/mol and 40.0 ± 0.5 kJ/mol. These values are classified as reversible trapping sites, since they are lower than 60 kJ/mol. The desorption activation energy of the non-loaded sample presented one value which is higher than 60 kJ/mol. This value is 40 % higher than the quasi-static loaded sample and was ascribed as irreversible trapping site. The desorption activation energies of the dynamic loaded were 20.0 ± 0.5 kJ/mol, 30.0 ± 0.5 kJ/mol and 72 ± 2.0 kJ/mol. Its higher activation energy value (72 kJ/mol) was classified as irreversible trapping site. The irreversible trapping sites were ascribed to \(\sigma\) phase formation and thier wide range (67-72 kJ/mol) were ascribed to \(\sigma\)'s phase density and hydrogen content in it. The dynamic deformation caused hydrogen to be trapped deeper in trapping sites (high energy trapping sites). However, at this dynamic pressure ~0.5 GPa the dislocation velocity was not fast enough to break-away from hydrogen [4], and hydrogen was still enable to escape. This occurrence enabled hydrogen to escape from deeper potential trapping site to less deep. This explanation is supported by the microstructural observations after dynamic experiments, Fig. 2 b [16], which showed massive cracking for dynamic loaded sample compared with non-loaded sample, Fig 2 a. These results support hydrogen embrittlement at high strain rate (10-5 s-1 at 0.5 GPa). The dynamic loaded hydrogenated sample showed intense cracking due to hydrogen's ability to escape from trapping site and promote cracking. This phenomenon is supported by other works which confirm that the susceptibility to hydrogen will depend on the competition between reversible and irreversible traps [24].

4. Summary and conclusions

This study examines the effect of low and high strain rates (10-7 s-1 and 105 s-1, respectively) on hydrogen charged and non-charged LDS. Quasi-static experiments showed an increment of ~20 % in yield strength which was related to the experiment deformation rate; higher deformation rate will not allow for enough time for hydrogen diffusion. This statement is well pronounced at dynamic experiments which did not show any effect of hydrogen on dynamic yield strength, \(\sigma_y\).

The hydrogen trapping energies of the quasi-static loaded (~10-7 s-1) sample were ~40 % lower than the non-loaded LDS sample and ~45 % lower than the dynamic loaded sample. At quasi-static loading, hydrogen had enough time to escape from the...
irreversible trapping site- ω phase, created during gas-phase hydrogen charging. The differences between the activations energies of the rest of the samples were belonged to ω phase density and deformation response which is responsible for hydrogen trapping. The greater deformation which was formed at experiments caused hydrogen to be trapped deeper in trapping sites (high energy trapping sites). Hydrogen embrittlement model is also seen and valid in the dynamic loaded sample and indicates on the same behaviour of hydrogen at low and high strain rate (10^7 s^-1 and 10^5 s^-1 at ~0.5 GPa).

References

A calculating sheet to optimize the design of modified Turkey Oak wooden laminated floors

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Abstract

The use of wooden floors has been for millennia the “compliant solution” for the horizontal elements of the most different types, due to their lightness, elasticity, resistance, flexibility of use and ease of realization. Recently, in particular for buildings located in seismic areas, it has been argued that their deformability was a serious defect and not only in literature, but also in the Official Rules, it is recommended or required that both the existing wooden floors, and new ones, should be made infinitely rigid and non-buckle able in their plane, through the application of reinforced concrete slabs, tied through connectors to the wooden beams. This solution has, however, turned out to be worse than the disease that tried to cure, on one hand causing the rotting of the wooden parts in contact with the concrete, and on the other determining – under earthquake forces - torque such as to cause the collapse of parts of the walls, or of entire building units. At La.Te.C. - Laboratory of Building Technology - of the School of Engineering of the University of Basilicata, it is an ongoing complex research which investigates for years the use and improvement of forest resources of Basilicata and the possibility to use for various purposes in construction the essence of hardwood Quercus Cerris L. (Turkey Oak). The research performed till now has shown the great interest on the use of thermo-hygrometric “modified” Quercus Cerris to tackle the problems set by the refurbishment and/or the restoration of buildings in the historical centres; it has been developed a construction system for wooden floors, based on the use, in addition to the traditional floor joists in vertical planes, of trusses of considerable height and therefore very rigid, arranged beside the external walls or internal ones in horizontal plane, with hinge tie at the ends to wooden chains bound to the perpendicular walls. These reticular trusses are able to retain rigidly in their position the external walls subject to seismic action, preventing from their tilting out of their plane, and then forcing them to express all the shear strength or buckling resistance of which they are capable. To facilitate the use of this system by the designers, it has been arranged and implemented a calculating sheet, upgraded to the most recent Italian Regulations.

Keywords: laminated hardwood Quercus Cerris, antiseismic timber floors, computer aided design

Introduction

The use of wooden floors has been for millennia the “compliant solution” for the horizontal elements of the most different types of buildings, due to their lightness, elasticity, resistance, flexibility of use and ease of realization. Recently, in particular for buildings located in seismic areas, it has been argued that their deformability was a serious defect and not only in literature, but also in the Official Rules, it is recommended or required that both the existing wooden floors, and new ones, should be made infinitely rigid and non-buckle able in their plane, through the application of reinforced concrete slabs, tied through connectors to the wooden beams.

This solution has, however, turned out to be worse than the disease that tried to cure, on the one hand causing the rotting of the wooden parts in contact with the concrete, and on the other determining - under earthquake forces - torque such as to cause the collapse of parts of the walls, or entire building units. Today is vigorously back of interest the use of wood, as a par excellence sustainable material (Lembo & Marino, 2015); and this especially for the hardwoods, given their superior structural quality and durability, and for the thermo-hygrometric treatments, that can substantially enhance the traditionally deemed "problematic properties of such essences" as for the Quercus Cerris L. (Turkish Oak), which constitutes a fundamental part of the landscape of large areas the Mediterranean, and that could prove to be a renewable resource of great importance to the inland areas of Southern Italy.

This current renewed interest led the La.Te.C. – Laboratory of Building Technology, active in the School of Engineering of the University of Basilicata – Potenza (Italy), on the one hand to develop a thermo-hygrometric treatment method specific for the Turkish Oak wood that, through the use of healthy structural adhesives, allows the realization of laminated timber elements capable of operating bending strains of 40.9 N/mm² (Marino, Lembo et al., 2006; Lembo & Marino 2007); on the other hand to develop a construction system for wooden floors, based on the use, in addition to the traditional joists in vertical planes, of trusses of considerable height and therefore very rigid, arranged beside the external walls and internal ones in horizontal plane, with hinge tie at the ends to wooden chains bound to the perpendicular walls (Lembo & Marino, 2008). These reticular trusses are able to retain rigidly in their position the external walls subject to seismic action, preventing their tilting out of their plane, and then forcing them to express all the shear strength or buckling resistance of which they are capable. These trusses, in relation with the high performance of laminated hardwood timber in which they are made, may have a thickness of only 8 cm, and then can occupy the thickness of the previous lime “gretonato” and “cocciopesto”, traditionally present in old buildings as floorings or...
under floorings; they are permeable to vapor (do not produce the root of the underlying planking) and can be included in a package of high efficiency to the impact sound; they allow wooden floors to keep the deformability that is their characteristic, thus safeguarding the masonry structure by twisting effects (Lembo, Marino & Cennamo, 2007). To facilitate the use of this system by the designers, it was developed a calculating sheet, upgraded to the most recent developments in Italian Regulations, which allows to optimize the calculation of this innovative type of floor, which can be used both in refurbishment actions, that for new construction in seismic areas, allowing wooden floors to last indefinitely. It has been used in case studies that are shown (Lembo & Marino 2007).

**Mechanical properties of Turkey Oak laminated wood, modified by thermo-hygrometric treatment**

The mechanical properties of the wooden elements of Basilicata's Turkish Oak modified by thermo-hygrometric treatment to realize glued laminated beams (Marino, Lembo et al., 2006), have been determined on the basis of experimental laboratory tests, as required by current Italian legislation (NTC2008, 11.7.4.2.2), and are the following (see Tab.1):

| Table 1. Mechanical characteristics of Turkey oak laminated wood - La.Te.C. Unibas |

It can be observed that its properties are many times higher than those of the laminated wood elements made from coniferous wood.

**Design of suspended floors**

Typical suspended floors hypothesized (see Fig.1) are (till to 4.50 m span) (flange deflection < 1/400) (bottom up):

- laminated Turkish Oak 1,00 m;
- Turkish Oak modified solid;
- impact sound insulation:
  - horizontal trusses in cm thick, 6 cm filled with:
  - plywood 1,2 cm thick;

![Fig. 1. Design of the typical suspended floor - laminated Turkish Oak joists 17 x 24 cm, distance between centers:}

- synthetic sheeting, 1,5 mm;
- elasticized EPS for impact sound and thermal insulation 3 cm thick, with radiant heating;
- heavy screed in concrete with stainless steel fibers, 2 cm thick;
- resin finishing.
Total weight, with internal plasterboard partitions: 2 kN/m$^2$. Live load, for residential use: 2.00 kN/m$^2$.

The calculation sheet allows the design and expeditious verification (flexural, shear and long term deflection) as required by the aforementioned Standards.

In a masonry building subjected to earthquake, as said, it is particularly important to prevent the tipping out of their plane of the walls, maintaining the deformability of the floors. Thus, it was conceived the new floor model designed and engineered by La.Te.C. (see Fig. 2):

![Trusses of Turkey Oak laminated wood in horizontal plane, inside the floor thickness](image)

Trusses act as very stiff braces, fixed with hinges at the ends; they prevent the flexural deformation of the walls (especially of external one) under action of seismic forces perpendicular to their plan, constraining them by chains going through and ribbed tie plates by their knots.

Calculation sheet allows to apply quickly masses and hence correspondent seismic forces (see Fig. 3):

![Some screenshots of the calculating sheet for the design and calculation of Turkey Oak laminated wooden trusses](image)

Once you choose truss structural typology with relation to the wall length (see Fig. 4), you determine real dimensions of truss, that is the rod’s length, the axial stresses and loads on the knots, using auto-vectors, calculus which has been performed through a finite element program, considering structural schemes in which rods have unit length.

![Classification of the truss beams in relation to their length and forces on their knots](image)
In all typologies rods have the same angle of descent; their number and length vary. The calculation sheet directs next steps, with verifications requested by the Standard NTC 2008, Cap. 4.4.8, with regard to the tensile and compressive strength of wooden elements and with regard to the design of joints, tie plates, bolts and nuts in stainless steel.

3.1. Case study of new building: “the old glassworks house” at Utscheid (D), 1986, design of Oswald Mathias Ungers.

The building system shown (see Photo 1) has been applied to a famous example of contemporary architecture, “the old glassworks house” at Utscheid (D), designed in 1986 by Oswald Mathias Ungers, German architect and architectural theorist, known for his style characterized by geometric rigor.

The application of the calculation sheet to a typology so regular has been very simple and direct (see Fig.5).

Fig. 1. The “house of the old glass factory” in Utscheid (Germany): view from the southwest
Fig. 5. Masonry building of small elements in seismic areas: (a) union framework of the trusses beams; (b) particular of the reticular structure; (c) cross-section; (d) longitudinal section

**Case study of restoration: Youth Hotel in the former Lagonegro (PZ) prison, 2016.**

It is the same for interventions on historic buildings, in which the conservation is the first goal (see Fig.6).

![Image of Lagonegro prison and restoration design](image)

Fig. 6. The former Prison of Lagonegro (PZ): (a) render of the restoration design; (b) current state; (c) arrangement of the trusses in the thickness of the suspended floors; (d) roof in the restoration design

**Roofs design**

With the same logic it is possible to design roofs and king-post trusses at the same time rigid (for taking in place front walls) and buckle able in plan, with Turkish Oak modified laminated trusses of very restrained dimensions (see Fig.7).

**Results and conclusions**


To employ buckle able floors entails an isostatic distribution of seismic forces, irrespective of walls stiffnesses. Thanks to his very high strength, to the capacity of buckling in plastic range with high ductility values, to the quality of dissipate energy by mechanical joints, to the great dimensional precision it allows, along with possibility of being easily and economically “purpose made”, and of making structural elements suitable for more different purposes, the hardwood Turkish Oak modified laminated allows to make resistant and buckle able floors, quite similar in appearance to ancient ones, of great appeal because of beige-amber pink color, almost endlessly durable, as the ancient one.
Fig. 7. The system of trusses on the roof, in Turkey Oak laminated wood: (a) constructive detail external wall-roof node; (b) positioning of trusses in the roof and their projection on the cover plan; (c) perspective view of the truss-floor joints system; (d) isometric view of the trusses on the roof, indicating the bracing on the roof

Contributions

Prof. Filiberto Lembo has coordinated and provided the objectives of the research. Msc. Eng. Francesco Paolo R. Marino has developed methodological and operational tools and verified search results. Msc. Eng. Giuditta De Filpo and Michele Cammarelle have done specific analysis in their thesis degree.

The contribution of the authors in editing and writing the text of the paper, was equal.

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Poor Quality Increases Industrial Pollution

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Abstract

A turning point of environmental pollution was the industrial revolution, due to the dramatic increase in the scale of pollutions of all sorts: air, water, etc., and industry is a major source of pollution ever since. Industrial pollution is strongly correlated with the volume of operation; large plant pollutes more than smaller plant. Further, industrial waste is a major part of the industrial pollution. It turns out that poor quality is a major cause for enlarged industrial operations and waste. A direct consequence is of defective items. A defective item is an item that cannot be used as is as intended to. It needs either to be repaired, reworked or replaced by another item. Each of these solutions requires additional production capacity, that is more pollution. Often, the defective item is wasted, as a whole or partially. An indirect consequence of poor quality results from the use of inspections to improve quality by removing defective units. Inspections, like manufacturing processes are imperfect. Manufacturing processes make defective items and inspections involved errors, particularly, false rejections. The manufacturing system is blind to see if a rejected item is defective or falsely rejected and the results are the same: enlarged operation and waste. In this study, these effects are quantified. Their orders of magnitude are overwhelming.

Introduction

"During most of our time on Earth we have kept it fairly clean and did not begin to damage the environment until very recently. Indeed, until the middle of the nineteenth century there was relatively little pollution." (W.A. Turmeau, Chairman, Scottish Environment Protection agency in his forward to Environmental Pollution Studies by Gerry Best, 1999) A turning point of environmental health was the industrial revolution. "The advent of the Industrial Revolution in the 18th century led to great increases in the use of natural resources such as fossil fuels." (Spellman, 2010) But not only use of natural resources, the industrial revolution led also to dramatic increases in the scale of pollutions of all sorts: air, water, etc., and industry is a major source of pollution ever since, "with the progress in technological and industrial pursuits, more pollutants have been added in the environment." (Shafi, 2005) Spellman (2010) also points to the correlation between the pollution and the volume of industrial operation; large plant is, generally a larger pollutant than smaller plant. Further, industrial waste is a major part of the industrial pollution. Hill (2010) explains that pollution occurs because "no process, natural or human, such as manufacturing or fuel burning, is 100% efficient; each produces pollution and waste, and wastes energy." A manifestation of inefficiency in the industry is poor quality. It turns out that poor quality is a major cause for enlarged industrial operations and waste. A direct consequence is of defective items. A defective item is an item that cannot be used as is as intended to, but in commercial operations there are sales targets and/or orders to deliver. "One of the customer's highest priorities is timely delivery of usable material." (Ptak, 2003) With regard to quality, whenever a unit is defective in a sense that it cannot be used as intended, it needs either to be repaired, reworked or replaced by another unit (e.g., Apple, 1963). Each of these solutions requires additional production capacity. These extensions were termed by Feigenbaum (1991) the hidden plant and adds to the pollution already generated by the visible plant. In addition, the defective item is often wasted, as a whole or partially.

An indirect consequence of poor quality results from the use of inspections to improve quality by removing defective units. Inspection, like manufacturing processes are imperfect. Manufacturing processes make defective items and inspections involved errors missing defective unit and false rejection of conforming units. The manufacturing system is blind to see if a rejected item is defective or falsely rejected and the result is the same a rejected unit cannot be used as intended and hence requires compensation. Moreover, this addition to the process's input adds defective units, too – the attempt to reduce waste results in more waste. Some comfort may be found in noting that in these regards, financial interests go in accordance with environmental concerns – the costs associated with the hidden plant can easily outdo the saving. These effects are quantified in this presentation.

Assumptions and basic calculations

The four assumptions of Eben-Chaime (2015) are assumed here as well:

- The work station for each activity/operation have already been selected;
- Activities/operations are independent;
• The processing of items in a station are independent;
• Long term averages are proper performance measures to use.

Assumption 1 is needed because the defect rate, the ratio of the number of defective units to the total number of processed units, is determined by both the activity and the work station where this activity is performed. Assumption 2 is rather reasonable because successive operations are performed in different work stations. Assumption 3 is justified by the prior (implicit) assumption that the process is in control, namely, defects are due to random causes, only. Under assumption 3, the mean number of conforming units produced by an operation with defect rate d, is the number of units processed less the defective units: Qout = Qin·(1-d). Consequently and following the observations above, in order to produce Qout conforming units, the minimal number of units that should be processed by each of the operations in a serial process of n operations is:

\[ Q_{in}^j = Q_{out}^{n-j} \prod_{i=j}^{n}(1-d_i), \quad j = 1, 2, ..., n \]  

(1)

These are minimal numbers as Eq. (1) is built on the assumption that each defective unit is detected and removed as soon as it becomes defective. This, of course, is an unrealistic assumption and, as pointed out by Eben-Chaime (2015) and as implied by Rodriguez-Verjan et al. (2011), many defective units continue through the system before they are detected and the quantities are inflated accordingly. As shown in the sequel, numerical examples can be constructed which demonstrate the colossal effects of the defective items items are processed, knowing in advance that many, and even most of them will turn defective. Even when each defect rate is small, they accumulate vary rapidly.

Paradoxically, attempts to fix the situation may worsen it! A defective item can be detected either in a coincidental manner or by inspection. Inspections, however, are, too, imperfect and involve errors. Type II errors refer to nonconforming items that are missed and slip through to proceeding operations. These items were referred to in noting that the numbers of Eq. (1) are minimal. Type I errors disqualifying conforming units, is of interest here. As noted, both defective and falsely rejected units cannot be used as intended and more units must be produced to replace them.

How bad is it? Suppose the type I error probability is \( \alpha \), then \( \alpha \cdot (1-d) \) of them are falsely disqualified. To illustrate, let \( d = 1\% \) and \( \alpha = 5\% \). Then, of 1,000 units, 10 are defective and another 49.5 units, about 5 times more, are falsely rejected, on average! No wonder, thus, that Type I errors are termed the producer’s risk (e.g., Montgomery, 2008). Further, there is another similarity between false rejections and defective items both accumulate along the production processes. Namely, if \( k_i \) inspections are introduced between operations \( j \) and \( n \) with type I error rate \( \alpha_i \), \( i=1, ..., k_i \), then Eq.(1) should be modified as follows:

\[ Q_{in}^j = Q_{out}^{n-j} \prod_{i=j}^{n}(1-d_i) \prod_{l=1}^{k_j}(1-\alpha_l), \quad j = 1, 2, ..., n \]  

(2)

Let the yield of a process be the ratio of conforming to the input units: \( Q_{out}/Q_{in} \), then the yield, \( y \), of a serial process of \( n \) operations with no inspections is obtained from Eq. (1) and equals \( \prod_{i=1}^{n}(1-d_i) \), while with \( K \) inspections Eq. (2) is used and \( y = \prod_{i=1}^{n}(1-d_i) \prod_{l=1}^{k_j}(1-\alpha_l) \).

Numerical illustration

Consider first, a process of 70 operations, with a defect rate of 1%, each. The yield of this process is about 50%. This implies that if 1,000 units are required, 2,021 units should enter the process. Note by passing the magnitude of nonconformance. Further notice the contribution to costs of this part of Feigenbaum’s (1991) hidden plant and the resultant increase in pollution and waste. Assuming that at least a final inspection is performed, whose false rejection rate, \( \alpha = 5\% \), the yield decreases to 47% and the input grows to 2,127.22 units, with no additional output, just more pollution and waste. Suppose six inspections are added, each with \( \alpha = 5\% \), say after each ten operations, as in; e.g., (Weber et al., 2002), (Rodriguez-Verjan et al., 2011). Then, the good intention results in a yield decrease to 34.55%. Consequently, the number of units that should enter the process, to yield 1,000 conforming units, grows from 2,127 to 2,894, knowing in advance that 1,894 units will not be used after the first pass through the process. Of the 2,894 units that enters the process, 276.72, on average, are defective after 10 operations – upon arrival to the first inspection. If the rate of type II error is \( \beta = 5\% \), too, about 13.84 of these defective units slip through the screening. Another 130.86 units are falsely rejected in this inspection. Thus, on average, only 2,500 units, including about 14 defective units continue. Of the 2,486 conforming units, some 2,249 are still conforming upon arrival to the next inspection. This pattern continues, as portrayed in Table 1, until the last inspection, which falsely rejects 52.63 units before passing the required 1,000 units, plus 6 defective units that managed to slip through all seven inspections.

Table 1: A serial process of 70 operations with 7 inspections

<table>
<thead>
<tr>
<th>Inspection</th>
<th># Conforming</th>
<th># Defective</th>
<th># False</th>
<th># Slip</th>
<th># Conforming</th>
<th>Total #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


With a single final inspection 56.36 defective units slip through. Namely, the additional inspections reduced this number by almost 10 times — an order of magnitude. However, this came at the expense of additional 767 units (2,894 - 2,127), 36% that are wasted, but only after emitting the associated pollution, and 6 more inspections, which might be extremely expensive.

Next, consider a longer process, with 100 operations. With a single final inspection, the yield is 34.77%. Hence, 2,876 units should enter the process to output 1,000 conforming units and about 94 defective units will slip through. The flow through the process when 9 inspections are added, one after each ten operations as before, is portrayed in Table 2. The pattern is very similar to that of Table 1.

Table 2: A serial process of 100 operations with 10 inspections

<table>
<thead>
<tr>
<th>Inspection #</th>
<th># Conforming</th>
<th># Defective</th>
<th># False rejections</th>
<th>Total # moved on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4126.64</td>
<td>436.30</td>
<td>206.33</td>
<td>3920.31</td>
</tr>
<tr>
<td>2</td>
<td>3545.46</td>
<td>396.67</td>
<td>177.27</td>
<td>3368.18</td>
</tr>
<tr>
<td>3</td>
<td>3046.12</td>
<td>341.89</td>
<td>152.31</td>
<td>2893.82</td>
</tr>
<tr>
<td>4</td>
<td>2617.12</td>
<td>293.80</td>
<td>130.86</td>
<td>2486.26</td>
</tr>
<tr>
<td>5</td>
<td>2248.53</td>
<td>252.42</td>
<td>112.43</td>
<td>2136.10</td>
</tr>
<tr>
<td>6</td>
<td>1931.85</td>
<td>216.87</td>
<td>96.59</td>
<td>1835.26</td>
</tr>
<tr>
<td>7</td>
<td>1659.78</td>
<td>186.33</td>
<td>82.99</td>
<td>1576.79</td>
</tr>
<tr>
<td>8</td>
<td>1426.02</td>
<td>160.09</td>
<td>71.30</td>
<td>1354.72</td>
</tr>
<tr>
<td>9</td>
<td>1225.18</td>
<td>137.54</td>
<td>61.26</td>
<td>1163.92</td>
</tr>
<tr>
<td>10</td>
<td>1052.63</td>
<td>118.17</td>
<td>52.63</td>
<td>1005.91</td>
</tr>
</tbody>
</table>

The number of defective units that slip through at the end is 6, as in Table 1. The number of units that should enter the process is 4,563 and the average number of units that flow through the process is 2,542.

Conclusions

In sum, poor quality adds to industrial pollution in several ways. First, defective units are often wasted, at least partially. Second, since non-conforming items need to be compensated for, the production capacity is extended to make these compensations. The plants are of larger size, the use of energy increases, etc. and the pollution and damage to the environment increase accordingly. Finally, inspections are introduced to improve outgoing the quality. The outgoing quality increases with the additional inspections but at the expense of lower yield, which forces to increase the input and process much larger quantities; i.e., higher pollution. In addition there is more waste — material loss, both more defective units and additional units that are falsely rejected. The major conclusion of this study is that it is better to reduce the number of defective units as much as possible, rather than removing them. This implies that better alternatives such as process monitoring in a level that enables close to 0 defect rates (e.g., Mandroli et al., 2006) should be searched for.

A point of light is this context is the fact that the processing of all these additional units costs a lot. Larger infrastructures are required, and more materials, energy and other resources are consumed. These all require huge capital. Hence, it is very much in the owners interest to reduce cost by improving quality. One only need to properly presents reality to them.

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The linearization method of positional response curve of the fiber-optic displacement sensor

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Abstract

Currently, one of the most actual problems in measuring technique is the creation of optical instruments for measuring of linear displacement. The most interesting fiber-optic sensors based on the magneto-optical effect. They are essentially contactless, non-electrical and have closed optical channel resistant to contamination. The main problem of this type of sensors is the non-linearity of positional response curve due to the hyperbolic nature of changing of the magnetic field intensity induced by moving magnetic source mounted on the controlled object relative to the sensing element. This paper discusses the algorithmic method of positional response curve linearization for fiber-optic displacement sensors in any selected range of measured displacements. The method is divided into two stages: 1 - definition of the calibration function, 2 – measurement and linearization of positional response curve (including its temperature stabilization). This algorithm significantly reduces the number of points of the calibration function due to usage of the points randomly deviate from grid points with uniform spacing. Subsequent interpolation of deviating points and piecewise linear-plane approximation reduces the amount of microcontroller memory for storing calibration function and the time required for processing of measurement results. This paper also presents test data of real samples of fiber-optic displacement sensors.

Keywords: Positional response curve; algorithmic linearization method; fiber-optic; displacement sensor; calibration function.

1. Introduction

Currently, one of the most actual problems in measuring technique is the creation of optical instruments for measuring of linear displacement [1-5]. The most interesting fiber-optic sensors (FOS) based on the magneto-optical effect. They are essentially contactless (non-mechanical contact with controlled object), non-electrical (does not contain electrical components in sensing element and does not require electrical power) and have closed optical channel resistant to contamination.

The main problem of this type of sensors is the non-linearity of positional response curve (PRC) due to the hyperbolic nature of changing of the magnetic field intensity induced by moving magnetic source mounted on the controlled object relative to the sensing element [6-16].

Figure 1 shows the dependence of the output signal versus the displacement of typical FOS sensing element based on the Faraday magneto-optical effect in epitaxial films of yttrium iron garnet [1].

Fig. 1. FOS output signal versus displacement.

2. The structure and operating principle of displacement FOS

Figure 2 shows a block schematic diagram of a differential FOS, based on the magneto-optical effect in epitaxial films of yttrium iron garnet (YIG). FOS consists of a laser diode (LD), a Wollaston prism (WP), YIG on a transparent sapphire substrate
and two film polarizers oriented relative to each other at angles of ± 45 degrees (FP1 and FP2). LD has a local stabilization circuit of temperature and radiation power. Electronic converter (EC) of FOS consists of photodiodes (PD1, PD2) and amplifiers of their output signals.

![Fig. 2. The block schematic diagram of a differential FOS.](image)

Consider the FOS operating principle (Figure 2). The light beam from the light source LD with circular polarization by fiber optical cable enters to the WP, which splits the beam into two beams with orthogonal polarization 0° and 90°. Both beams pass through the YIG plate, which rotates the polarization plane of each beam to an angle proportional to the intensity of magnetic field induced on FOS. After YIG beams passes through the polarizers FP1 and FP2, initially configured to +45° and -45° for each branch of sensor. The resulting optical signals of FOS are applied to respective photodiodes of EC, in which amplification and the mathematical processing are performed.

The output signal of FOS determined typically according to the following expression [14-15]:

\[
U(x) = \frac{U_1(x,t) - U_2(x,t)}{U_1(x,t) + U_2(x,t)}
\]

(1)

herein \( U(x) \) - dependence of the output signal on displacement;

\( U_1(x,t) = Y_1(x,t) \cdot k \), \( Y_1(x,t) \) - output electrical and input optical signals of PD1;

\( U_2(x,t) = Y_2(x,t) \cdot k \), \( Y_2(x,t) \) - output electrical and input optical signals of PD2;

\( k \) - conversion coefficient of the optical signal to an electrical by photodiodes PD1, PD2.

However, as shown by the simulation results (Figure 3), formula (1) is applicable only when the condition (2) (curves 1 and 2 in Figure 3):

\[
U_1(x,t) + U_2(x,t) = \text{Const}
\]

(2)

In terms of violation (2) there is a sharp distortion of FOS PRC (curves 3 and 4 in Figure 3) and the deterioration of the multiplicative error compensation using the expression (1).

An algorithm described in this paper is devoid of these weaknesses.
3. The method of calibration and linearization of FOS PRC

Calibration function is determining the correspondence of argument (FOS displacement and temperature) to FOS output signal, processing of measurement results and recording obtained dependence to the microcontroller (MC) memory. In the measurement mode is carried out the linearization and temperature correction of the measurement results.

In addition, this algorithm significantly reduces the number of points of the calibration function due to usage of the points randomly deviate from grid points with uniform spacing. Subsequent interpolation of deviating points and piecewise linear-plane approximation reduces the amount of microcontroller memory for storing calibration function and the time required for processing of measurement results.

The method is divided into two stages:
1. definition of the calibration function of FOS,
2. measurement and linearization of positional response curve (including its temperature stabilization).

3.1. Definition of the calibration function of FOS

To calibrate the sensor in the microprocessor memory is recorded positional response curve of FOS. This calibration is carried out for a relatively small number of points (16 to 64 points in each variable) $F(x; t)$. Consider FOS calibration for some portion of the PRC (Figure 4). Let experimentally were obtained following points of PRC: $U_{i,j}^R(x_{i,j}^R ; \bar{t}_{i,j}^R)$, $U_{i+1,j}^R(x_{i+1,j}^R ; \bar{t}_{i+1,j}^R)$, $U_{i,j+1}^R(x_{i,j+1}^R ; \bar{t}_{i,j+1}^R)$, $U_{i+1,j+1}^R(x_{i+1,j+1}^R ; \bar{t}_{i+1,j+1}^R)$, herein $U_{i,j}^R(x_{i,j}^R ; \bar{t}_{i,j}^R)$ – output voltage of the amplifiers connected to the PD1, PD2 photodiodes, which are located in the FOS electronic converter, [mV]; $x_{i,j}^R$ – predetermined value of linear displacement, [mm]; $\bar{t}_{i,j}^R$ – predetermined value of temperature, [$^0 \text{C}$]; $i, j$ – number of points on the displacement and temperature axis, respectively; $R$ – index indicating experimental data.

Obviously, the experimental values may not match with the specified units of measurement grid (grid nodes are usually set at a constant pitch $\Delta x = \text{const}$, $\Delta t = \text{const}$).

Therefore, during the calibration procedure is carried out piecewise surface (linear or non-linear) interpolation (or extrapolation) of a predetermined order and calculated values of the calibration function $U_{i,j}^R(x_{i,j}^R ; \bar{t}_{i,j}^R)$ in the adjacent grid points (Figure 4):

$$U_{i,j}^R(x_{i,j}^R ; \bar{t}_{i,j}^R) \rightarrow U_{i,j}^R(x_{i,j}^R ; \bar{t}_{i,j}^R)$$

(3)
Since the FOS does not contain built-in temperature sensor, and there is no way of determining the temperature explicitly, the change of temperature of the FOS sensing element can be taken into account implicitly (2) according to the change of function value \( F_{i,j}(x_i,t_j) \) (for \( i, j \) = grid points):

\[
F_{i,j}(x_i,t_j) = U1(x_i,t_j) + U2(x_i,t_j) \Rightarrow t_j = F^{-1}_{i,j} [U1(x_i,t_j) + U2(x_i,t_j)] ,
\]

wherein \( F^{-1}_{i,j} \) - inverse function of \( F_{i,j} \). Hereinafter arguments \( x_i,t_j \) for simplification are replaced with numbers of grid points \( i, j \).

Usually, the development of industrial sensor applications used operating temperature range (0 ... 50) °C. In the case of determining the calibration function of PRC with 10 °C pitch obtains 6 reference points on the temperature axe \( j = 0...5 \). For the displacement range (0 .. 31) mm and a 1 mm quantization step obtain 32 reference points on the displacement axe \( i = 0...31 \). In this case, to store the calibration function of PRC in the space of two variables \( x_i,t_j \) need 192 points of the function values \( U2_{i,j} \).

### 3.2. Measurement and linearization algorithm of PRC

The measurement mode is carried out linearization of FOS PRC and temperature correction of the measurement results:

1. Voltage values \( U1^R(x) , U2^R(x) \) of the electronic converter amplifiers connected to the FOS are measured.
2. The nearest grid points of \( i, j \) for the measured voltage values are defined:

\[
U_{i,j}^R(x_i,t_j) \in [U_{i,j}(x_i,t_j),U_{i+1,j+1}(x_{i+1},t_{j+1})].
\]

3. Calculate temperature of the nearest grid point from equation (4).
4. Determines the temperature deviation from the nearest grid point:

\[
\Delta t_i = (t_i^R - t_{i,j}).
\]

5. Using linear interpolation to implement temperature compensation of voltage values:

\[
U1^R(x,t) \rightarrow U1^C(x) , \ U2^R(x,t) \rightarrow U2^C(x),
\]

wherein \( U1^C(x) , \ U2^C(x) \) – measured voltage values after temperature correction.
6. The PRC calculated from CC using inverse function of PRC:

\[
x = x_i + U^{-1}[\Delta U_{i,j}^C(x)],
\]

wherein \( \Delta U_{i,j}^C(x) = U1^C(x) - U2^C(x) \). Thus, the PRC linearization carried out.
7. Then scaling of the obtained values range is performed to the full measurement range of the argument \( x \in [x_{\text{min}}, x_{\text{max}}] \) (for example, to the range \([0 ... 4095]\)). The result is ADC digital code \( \text{ADCcode}(x) \) of converter microcontroller corresponding to the displacement:

\[
\text{ADCcode}(x) = 4095 \frac{x-x_{\text{min}}}{x_{\text{max}}-x_{\text{min}}}
\]
4. Experimental study

Experimental studies were carried out on displacement FOS samples SAM.FOS.YIG-2/50, developed in the laboratory NIL-53 of Samara University (Figure 5). The experimental results are shown in Figures 1, 3, 6. Figure 6a shows the FOS PRC (curve 1), supplied to the input of the electronic converter, and digital result code (curve 2). There linearization carried out on the site of displacement [20 ... 32 mm] (site of displacement can be anything in the range [0 ... 32 mm]). Figure 6b shows the same FOS PRC after linearization on an enlarged scale. This algorithm makes it easy to move the operating range of linearization PRC to any part of the displacement range including the entire range. Designed FOS (SAM.FOS.YIG-2/50) has the following operating characteristics (table 1).
5. Conclusions

1. The virtue of the developed technique and an algorithm is that linearization and scaling can be performed in any range of the measured displacements \( x \in [x_{\text{min}}, x_{\text{max}}] \) and temperatures. This allows to calibrate FOS by simple way on controlled object and speeds up the calibration process, that is essential in case of mass production of FOS.

2. Experimentally confirmed high linearity of PRC – PRC nonlinearity does not exceed 0.01% in a range of displacements from 0 to 50 mm.

3. Experimentally confirmed high temperature stability of FOS – temperature coefficient does not exceed 0.0025%/°C in the temperature range from 0 to +50 °C.

References


Experimental study of the polarization transformation of semiconductor lasers in fiber-optic elements of the optical polarization sensors

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Abstract

At present, in fiber-optic sensors of polarization type the optical fiber is used both as the sensitive element (SE), and as the fiber-optical communication lines (FOCL) for transmitting of an optical signal. In such sensors there is the need to matching the polarization axes of the optical radiation source (ORS) and the SE. However, the FOCL elements located between ORS and SE are making their own polarizing distortions due to the anisotropy of optical properties of fiber resulting from bending deformations that have random character. This reduces the accuracy and repeatability of the polarization sensor (PS) measurements. The offered method of polarization correction consists in depolarization (transformation to circular polarization) of optical radiation by placing between ORS and SE optical fiber coil with certain parameters: diameter of the coil, number of rounds and an angle of the coil rotation relative to the plane of ORS polarization. This method allows to exclude from an optical path the expensive optical elements (for example, quarter-wave plates) and to simplify the design of the sensor/measuring device. During experiments it was found that in this way the polarization can be reduced from initial 17 dB to 0.8 dB.

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Keywords: Polarization sensor; polarization correction; semiconductor laser; optical fiber; bending deformations.

1. Introduction

In fiber-optic polarization sensors the optical fiber is used both as the sensitive element (SE), and as the fiber-optical communication lines (FOCL) for transmitting of an optical signal. As a source of optical radiation (ORS) is used quite often a semiconductor laser diode having an elliptic, rather often close to the linear polarization. The main complexity in polarization sensors manufacturing is matching of polarization axes of ORS and polarizers of sensitive element (SE) of the sensor.

Besides, polarization change by the sensor elements which aren't a part of a measuring path, for example, as a result of bending deformations of optical fiber of FOCL, SE and ORS, reduces the accuracy and repeatability of measurements. Therefore, there is a need of their minimization or full elimination.

It is known that bending characteristics of optical fiber depend on light polarization plane with respect to the bending plane [1]. Therefore, the total change of polarization in FOCL is determined by tracing of an optical fiber on object of monitoring and has random character. The way out of this situation is the «depolarization» (conversion to circular polarization) of optical radiation before the SE.

Typically, optical radiation with circular polarization from radiation with an arbitrary polarization or natural light is received the next way: at first will transform radiation into linearly polarized, and then, for example, by means of a quarter-wave plate, into radiation with circular polarization [2-7]. Usually as a quarter-wave plate use anisotropic crystals, possessing property of birefringence. The disadvantages of this method are:
- the high cost of quarter-wave plates;
- the need of precise centering of a light source and receiver;
- the compelled light conclusion from fiber into the air, that leads to additional losses of optical power.

This work is devoted to the experimental investigation of a possibility of polarization correction of optical radiation by inclusion in an optical path of the sensor before SE of the deformed optical fiber segment, in which occurs an anisotropy of the optical properties, and as a result, the birefringence [8-15].

2. Experimental study

2.1. Experimental studies of optical radiation polarization of LD

To study the polarization effects the universal stand (fig. 1), which allows to research both the polarization characteristics of the separate elements and the entire sensor, was developed. The stand consists of: power supply of the laser diode (PS); the laser diode (LD) with a fiber output LDI-650-FP-20, produced by LLC «LasersCom»; two segments of a connective optical fiber such as patch cord (CF1, CF2), terminated on the one hand by the optical connector FC/UPC, and the other – the collimating graded-index lens (GRIN1, GRIN2) for an output and input of optical radiation; the optical fiber coil fixed on motorized rotation platform of a certain diameter with a certain quantity of an optical fiber rounds (ROFC); the film polarizer fixed on an external
bearing ring and rotating by means of electric stepper motor (RFP), wherein the inner bearing ring is set on the sleeve which mounted on an optical plate; the stepper motors controller (SMC) for the ROFC and RFP; power meter of the optical radiation (OPM) FOD1202 produced by Fiber Optical Devices; the photodiode (PD) connected to an oscilloscope (OSC).

![Fig. 1. block diagram of the experimental stand: (a) for research of LD polarization and polarization change in FOCL; (b) for research of polarization change in the deformed optical fiber.](image)

For the study of LD polarization characteristics used the option of stand configuration shown in a fig. 1(a). Radiation of LD is injected directly into GRIN1, and passing through RFP polarizer, is modulated the optical power amplitude, then the modulated light is entered into GRIN2 and arrives on the OPM. The results of an experimental study of the LD output optical power depending on the RFP rotation angle shown in Figure 2.

![Fig. 2. The polarization of the LD optical radiation.](image)

As seen in fig. 2 the optical radiation of semiconductor LD is sharply polarized, and the change in the LD optical power depending on installation of polarizer angle is reaches to 17 dB.

2.2. Experimental studies of the polarization changes in the FOCL

It is accepted that with a length of FOCL bigger than length of polarization beatings the optical radiation becomes depolarized [8-15]. For research of this phenomenon in an optical chain segment between LD and PD of already considered experimental stand (fig. 1 (a)) instead of CF1 joined rather long single-mode (SM) fiber (optical fiber cable PVC SM 9/125 2.0 mm OFNR) or multimode (MM) fiber (Corning OM3 Fiber optical cable LSZH type CO-PD-23) with a length of 50 m, curtailed into a bay of big diameter (40 cm). Results of an experimental study are given in fig. 3. For comparison the polarization characteristic of the LD is shown.
On Fig. 3 the curve 1 represents the polarizing characteristic of LD received in the first experiment, a curve SM – the polarizing characteristic of radiation after passing through a bay of single-mode fiber, a curve MM - the polarizing characteristic of radiation after passing through a bay of multimode fiber. From comparison of dependences it is visible that passing of radiation through FOCL reduces the polarization of radiation, but it is not so strong, predictably. For single-mode 50 m FOCL the change of optical power depending on the angle of polarizer installation reaches 3 dB, and for multimode 50 m FOCL – 6 dB. It is obvious that the similar method of elimination of polarization radiation is a little effective for implementation in polarization sensors.

2.3. Experimental studies of the polarization changes in the deformed optical fiber

For research of influence of optical fiber deformation on polarization change in an optical chain segment between LD and PD (Fig. 1(b)) joined the coil with optical fiber (ROFC) mounted on a rotary platform, and equipped with the optical connector on the one hand and a the collimating graded-index lens (GRIN1) on the other hand.

The operation principle: light from the LD enters into the fiber wound on a coil, which can discretely rotate on a certain angle (ROFC). As a result of the optical fiber deformation and the consequent birefringence there is a change of polarization of radiation [1]. Changing diameter of the coil, quantity of rounds of an optical fiber, a coil turning angle, the level of polarization of optical radiation is determined (by amplitude of the periodic signal fixed by an oscilloscope).

As an example, define the radius of the optical fiber coil possessing the properties quarter-wave plate. The phase difference on an output of the fiber is calculated according to the formula [1]:

$$\delta = \frac{2\pi^2 an d^2}{D \lambda},$$

(1)

herein $a$ - photoelasticity coefficient, $N$ - quantity of rounds of an optical fiber, $d$ - diameter of a fiber cover, $D$ - coil diameter, $\lambda$ - wavelength.

The diameter of the coil:

$$D = \frac{2\pi^2 an d^2}{\lambda \delta}.$$  

(2)

Considering that the difference of phases for a quarter-wave plate is $\pi/2$, find the coil diameter (for different wavelengths and quantity of rounds). The results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>650</th>
<th>850</th>
<th>1330</th>
<th>1550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical fiber type</td>
<td>SM</td>
<td>MM</td>
<td>SM</td>
<td>MM</td>
</tr>
</tbody>
</table>

Table 1. The calculated values of coil diameter.
As seen from the table the single-mode fiber requires either very small coil diameters or a large number of number of rounds. Experimental studies were performed on wavelength of 650 nm with a 20 mm diameter coil with different quantity of MM fiber rounds using stand with OPM shown in fig. 1(b). The dependence of the output optical power from the rotation angle of coil with a different quantity of fiber rounds is shown in fig. 4. The initial polarization change of LD was accepted equal 17 dB (fig. 2).

![Graph of optical power level vs. coil turning angle](image1)

**Fig. 4.** The dependence of polarization change on a coil turning angle.

As seen from the results of experimental studies it is possible to achieve the polarization reduction to 0.8 dB. Dependence of output optical power on a polarizer turning angle for an optimum inclination of the coil with optical fiber is presented in a fig. 5. In a figure points designated the experimental values, solid lines – approximation of the experimental values using polynomials of six degree.

![Graph of optical power level vs. polarizer angle](image2)

**Fig. 5.** Polarization characteristics of optical radiation for various coils with optical fiber.
3. Conclusions

Experimental studies suggest the following conclusions:
1. Semiconductor LD possesses essential (to 17 dB) polarization of radiation.
2. The FOCL up to 50 m allow reducing polarization of radiation from 17 to 3…6 dB.
3. The use after the FOCL before SE of coil with a MM optical fiber and its optimum inclination allows to reduce polarization of radiation from 17 dB to 0.8 dB, and sharing of the depolarization properties of long fiber optic coil and multimode fiber can reduce the total polarization to a value of 0.04 dB (calculated value).

References
Influence of composition parameters on the tunnel lining concrete made with dredged sandy sediments subjected to high temperatures

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Abstract

The objective of this experimental work is to investigate the fire performance of different concretes. Four concretes were made, an ordinary concrete named C1 with quarry aggregates and three concretes named C2, C3 and C4, with quarry aggregates and dredged sediments. C3 concrete contains silica fume and for C4 concrete silica fume and polypropylene fibres was added. Physical properties as weight loss, porosity and UCS resistance were determined under normal conditions at a temperature of 20°C and after heating at temperatures of 150°C, 350°C and 600°C. Mechanical tests after cooling operations were performed on samples to obtain residual UCS values. Results show that C3 concrete develops the highest UCS value at a temperature of 20°C. The weight loss increase for all the concretes that are heated is observed. C3 concrete reveals a minimal porosity value at all the temperatures tested. C3 concrete cooled in air has a peak strength at 350°C that is more pronounced than the other concretes. The effects of high temperature on concretes residual UCS are more observed when the concrete is subjected to a thermal shock in water than when cooled in air.

Key-words: Tunnel lining Concrete, Quarry aggregates, Dredged sediments, High temperature, Physical properties, UCS, Air and water cooling

1. Introduction

Concrete is widely used in tunnel lining structures but its properties must conform to the requirements of durability, rheological and mechanical performances. In order to increase these performances, modifications to the concrete composition have to be made by decreasing the ratio water/cement and by adding mineral additions [1]. Yet, these changes can induce the decrease of the concrete fire resistance [2].

Tunnels are vulnerable constructions on two points. First, when they are exposed to fire because confinement can induce a high increase of temperature inside the tunnel [3]. Second, two cooling regimes by water or in air can induce different effects [4].

As a matter of fact, the International Association of Road Committee on Road Tunnels (PIARC) [5] established that fires in tunnels can damage them because the temperature in the concrete tunnel lining rises quickly and can induce the spalling of the concrete. So, the thickness of the concrete diminishes and instabilities can appear in the tunnel. Recent studies have also shown that concrete residual performance decreases when the initial resistance increases [6, 7, 8 and 9], because high performance concretes are more sensitive to spalling than ordinary ones. The modification of concrete characteristics depends on the characteristics of its components [9] and its porosity [10, 11 and 12]. Two types of damage occur when concrete is exposed to fire. The first one is the degradation of the material whilst the second is the degradation of the structural performance. The analysis by DTA / GTA provides information on the material degradation and chemical changes that occur when the temperature increases [13 and 14]. A permanent weight loss is observed [15]. The degradation of the structural performance is observed by the spalling of concrete and its loss of strength. The most effective solution available to prevent the spalling of concrete is the incorporation of polypropylene fibers [16, 17, 18, 19, 20 and 21]. Other effects are also observed, such as changes in colour and the development of surface cracks [22].

Moreover, influence of cooling regimes is important when a fire is usually extinguished using water [4]. The difference between water and air cooling regimes on the concrete mechanical properties as well as on its pores structure has been reported by Luo et al. [4].

Concrete is a local material; its characteristics and its sustainability depend on its components. The advantage of this experimental work is to provide data about the residual mechanical properties of fiber-reinforced concrete made with different aggregates after heating and cooling in the air and by water. These properties are very important for the quantitative determination of the potential damage caused by fire and the structural damage assessment of a tunnel to achieve the design of a sustainably resistant concrete and also allow the repair work to be done after the fire.

2. Materials and methods

3. Materials

The concrete is a mix of aggregates, cement and water in which mineral additive, admixtures and fibers may be added.
Cement

The cement used is a blended Portland cement (Algerian standard [23], type II/A 42.5), produced by cement factory of Sig in the west of Algeria.

Table I shows its chemical and mineralogical compositions. It has a Blaine specific surface of 391.8 m²/kg and a density of 3100 kg/m3.

Aggregates

Quarry aggregates

The sand used is a 0/4 mm calcareous crushed sand from the Kristel quarry in East Oran. A correction of sand particle size was carried out so as to obtain a grain size distribution curve within the standardised range. This was done by adding siliceous fine sand from Terga in West Oran. The physical characteristics of the quarry sand, after correction, are given in Table II.

The coarse aggregates are crushed to obtain limestone aggregates; they are produced by the Kristel quarry with a maximum size of 16mm. Their physical characteristics are given in Table II. The grading curves of the quarry aggregates are drawn in Figure 1.

Dredged sediments

Dredged sediments (DS) used were collected from the port of Oran; their treatment and complete characterisation were carried out in a previous study [24]. Physical characteristics and chemical components of the DS are given in Table III. The average particle size distribution curve is provided in Figure 1. DS contain 6% of clays, 39% of silts and 55% of sands. The nature granulometry range is considered as follows, clay fraction < 2 μm, silt fraction from 2 μm to 63 μm and sand fraction > 63 μm.

Water

The water must be free of organic matter and sulphates and its acidity must be greater than 4. Chemical analysis of the tap water used reveals a value of pH 7.11 that is close to neutrality, with a very low organic matter content of 0.12 mg/L, and a low sulphate level of 115 mg/L.

Mineral additive

The physical and chemical characteristics of the mineral additive (Silica Fume: SF) are given in Table IV [25]. According to the European standard EN 13263-1 (2005) [26], the silica fume must have a standardized activity index (I28) greater than or equal to 1.00 at 28 days. Activity index (I28) is the ratio of the UCS of mortar with 10 % of SF, substituting 10% of cement, and the UCS control mortar at 28 days.

Admixture

The admixture used is super-plasticizer (SP) water-reducing non-chlorinated Viscocrete 3045 produced by Sika Industry. Technical data known are the following ones: pH 5 ± 1, relative density 1.11 ± 0.02 and dry extract 36.4% ± 1.8.

Fibers

The polypropylene fibers (PPF) used, are monofilament fibers produced by Sika Industry. The main fiber characteristics given are provided by the manufacturer. It concerns fiber's diameter 18 μm, fiber’s length 6mm, relative density 0.93, melting and vaporisation temperatures about 171°C and 341°C respectively.
4. Methods

5. Mix design of concrete

Compositions of concrete without fibers were formulated according to the requirements of the European standard EN 206 – 1[27]. This standard defines the exposure classes.

The exposure class refers to the environment wherein the concrete will be exposed during its service life. Operational underground structures may be exposed to the chemical aggressions of natural soils and ground waters but also to the carbonation. An XA3 exposure class was chosen because it has higher requirements than the XC4 class. After that, two assumptions have been considered to formulate concrete:

- The concrete is formulated to have necessary rheological characteristics and obtain the consistency criterion, in the fresh state.
- The concrete is formulated to have necessary mechanical characteristics and obtain the strength criterion in the hardened state.

Table V summarises all of the data for the ordinary concrete’s formulation of C1 concrete.

Preliminary studies made it possible to optimize the granular skeleton of concrete, which is kept constant in this study with a gravel-sand (G/S) ratio value of 1.7 ± 0.01. Two values of water–cement (W/C) ratio were determined, 0.45 for concrete mixes C1 and C2 and of 0.4 for C3 and C4.

The super-plasticizer (SP) was introduced into the composition of concrete mixes C3 and C4 to obtain the required rheological characteristics. Compatibility of the mixture cement-SP was tested on a mortar’s equivalent concrete. Results from tests have given a value of 1.5% for the saturation point. Then the concretes were tested with different values of super-plasticizer such as 1.5%, 1%, 0.75%, 0.5% and 0.25%. The optimal compositions were determined using a SP percentage of 0.5%. The optimum percentage of FS was determined in a previous study [25]. The polypropylene fibers have been introduced with a level of 2kg/m³ according to the European Standard EN 192-1-2 [28]. They are dispersed during the mixing. Table VI gives the optimised compositions of all concretes.

6. Experimental protocol

Twenty eight series of cubic “100mm3” specimens of concrete were made and named C20 for the concrete kept at the room temperature of 20°C, C150 for the concrete heated at a temperature of 150°C, C350 is the concrete heated at the temperature of 350°C and C600 for the concrete heated at a temperature of 600°C.

The cubic specimens of concrete were dried in an oven at a temperature of 40°C until the stabilization of their weight. Then they are heated at temperatures of 150°C, 350°C and 600°C in a muffle furnace with a heating rate of 10°C/min and kept at the chosen temperature for one hour and cooled in the closed furnace with the same cooling speed, i.e. 10°C/min. Then, they were protected in laboratory because their physical characteristics should not change.

The weight losses were determined at each heating temperature. The degree of dehydration, i.e. weight loss in %, is calculated as follows:

\[
\text{Weight loss in \%} = \left(\frac{M2 - M1}{M1}\right) \times 100
\]

wherein, M1 and M2 are the weights of the specimens before and after heating.

The cube-shaped test specimens “50 mm3” are prepared and used to measure the porosity for all the concretes using the procedure given in ASTM C642 [29].

At the end of a period of 150 days, twelve series of concrete specimens (100x100x100mm3) were heated at temperatures of 150°C, 350°C and 600°C respectively. Then they were cooled in air and then they were crushed to obtain the residual UCS values.

Another twelve series concrete specimens (100x100x100mm3) were heated at temperatures of 150°C, 350°C and 600°C respectively, and cooled by water. They were finally crushed to obtain the residual UCS values. Table VII summarises the number and type of cubic specimens made.

7. Results and discussion

8. Unconfined compressive strength (UCS) at temperature of 20°C

The mechanical behaviour of concretes with mineral additive at room temperature was studied [25]. Results obtained in this study are presented in Figure 2 that shows the change in the unconfined compressive strength (UCS) on cube–shaped test specimens.

The average values for UCS of the C1 specimens are equal to 34.5MPa at 7 days, 48.0MPa at 28days, 51.5MPa at 60days and 52.0MPa at 90days. A very small increase in UCS values for C2 specimens is observed, with 38.0MPa, 49.5MPa, 52.5MPa and 53.0MPa at 7, 28, 60 and 90days respectively. The influence of sandy dredged sediments is not observable. Concerning the C3
specimens, average UCS values reached 50 MPa at 7 days, 71.0MPa, 78.0MPa and 80.0MPa at 28 days, 60 days and 90 days respectively. The beneficial effect of silica fume is clearly noticed. C4 specimens, also composed with SF provide UCS values of 47.0MPa, 65.0MPa, 70.5MPa and 72.5MPa at 7 days, 28 days, 60 days and 90 days respectively, are lower than those of C3 specimens. This decrease in UCS is about 9% for all ages. The mechanical performance decreasing is due to the addition of polypropylene fibers. In fact, a poor adhesion between PPF and cement causes an increase in concrete cracking and consequently in the porosity [12, 16 and 30].

9. Loss of weight

Evolution of weight loss of different concretes according to temperature is shown in Figure 3. A permanent weight loss during the heating of all concretes is noticed. Also, the presence of PPF does not change the shape of curves. It is observed that the evolution of weight loss concretes corresponds to 3 steps. At a temperature of 150°C, weight losses are estimated at 3.83% for both C1 and C2 specimens, 3.10% for C3 specimens and 3.20% for C4 specimens. At a temperature of 350°C, values became equal to 5.61% for both C1 and C2 specimens, 4.40% for C3 specimens and 4.58% for C4 specimens. Finally, at a temperature of 600°C, these values reach 8.69% for both C1 and C2 specimens, 7.20% and 7.42% for C3 and C4 specimens respectively.

Variations in weight loss are observed. Differences between concretes can be explained. It is due to the difference in the amount of water in concrete. Weight losses result in the progressive dehydration of the concrete.

Water can go out more easily from both C1 and C2 specimens than from C3 and C4 ones. Up to a temperature of 150°C, the free water and part of weakly chemically bound water, i.e. adsorbed water, evaporate and capillary pores are dried. At a temperature of 350°C, the chemically water bound to the CSH and ettringite evaporates. The difference in the weight loss between C3 and C4 specimens is due to the melting of PPF. For a 600°C temperature, the strongly chemically bound water contained in Portlandite evaporates. The same variation between C3 and C4 specimens is shown; it is due to the vaporization of PPF.

At 600°C, C3 specimens have a weight loss of 7.20%, whilst C4 specimens have a weight loss of 7.42%. The difference of 0.22% is greater than the percentage 0.08% of PPF contained in C4 specimens. So, their vaporization does not explain this additional weight loss. Researchers agree that the additional weight loss is due to the cracking increase in concrete with PPF that affects the total weight loss of the sample [12, 15, 16 and 27]. During heating, the microstructure and properties of concretes are modified, thus affecting their porous structure.

10. Porosity

The porosity accessible to water has been measured at a temperature of 20°C, and after heating. Measured values are 4.10% for both C1 and C2 specimens, 2.33% and 2.90% for C3 and C4 specimens respectively. As said in section 2.2, concrete differs by their composition; C1 and C2 specimens were mixed with more water than C3 and C4 ones. C3 and C4 specimens contain a mineral additive: SF. Chemical analysis has shown that the mineral additive SF is a pozzolanic material. This pozzolanic property allows the fixation of lime and reduces the number of pores by CSH formation. This explains that C3 and C4 specimens have a lower porosity than C1 and C2 specimens. The porosity of C1 and C2 specimens differs by 43% in relation to C3 specimens, and there is a difference by 30% in relation to those of C4 specimens. It is observed that C4 specimens have a greater porosity than C3 specimens around of difference 24%. This increase in porosity is due to the presence of PPF.

The porosity rate according to temperature is shown in Figure 4. With increasing temperature, the porosity of C4 specimens is greater than C3 specimens. At a temperature of 150°C, the porosity is estimated at 6.00% for both C1 and C2 specimens, and 3.55% and 4.31% for C3 and C4 specimens respectively. At a temperature of 350°C, values became equal to 11.61% for both C1 and C2 specimens, and 8.83% for C3 specimens and 11.75% for C4 specimens. Finally, at a temperature of 600°C, these values reach 12.00% for both C1 and C2 specimens, 9.10% for C3 specimens and 12.12% for C4 specimens.

In the temperature range 150°C to 350°C, the increase in porosity is high for concretes without PPF, while for C4 specimens, a greater increase in porosity has been observed.

The shape of curves did not change with the addition of PPF, but there is an additional porosity that is confirmed by several researchers in their conclusions [12, 16, 19, 21 and 30].

Whatever the temperature considered, porosities of C1 and C2 specimens are greatest. The evolution of porosity does not follow the same kinetics of weight loss. The increase in pores volume has been observed between the temperature of 20°C and 150°C. This quick increase has been attributed to the free water loss.

In fact it increases up to a temperature of 350°C and then slows down beyond this temperature. The porosity generated by the departure of chemically bound water is very small. Beyond a temperature of 350°C, results show that during heating, the microstructure of concretes has changed and they become more porous. In C4 specimens, the melting and vaporization of PPF create an additional porosity and so the total porosity is greater than C3 ones. This porosity facilitates the moisture flow, reducing the internal pressure, described by some authors as a factor of the concrete thermal instability [2, 16 and 17]. These physical characteristics as the weight loss and the porosity change and will influence the mechanical properties of concrete.
11. Residual unconfined compressive strengths

Residual UCS of concretes and their changes during heating were studied. Residual UCS of concretes heated at different temperatures and subjected to thermal shocks in air or in water was measured. It is observed that at a temperature of 150°C, the residual UCS of both C1air150 and C2air150, C3air150 and C4air150 specimens represents 78%, 82% and 80% of the UCS of C120, and C220 specimens, C320 specimens and C420 specimens respectively. After 150°C, there is a slight increase in the UCS of C1air350, C2air350, C3air350 and C4air350 which reaches, at a temperature of 350°C, 74%, 89% and 78% of concrete C120, and C220 C320 and C420 respectively. The decrease is quasi-linear, and the UCS of concrete C1air600 and C2air600, C3air600 and C4air600 was 32%, 31% and about 32% of the UCS of both C120 and C220, C320 and C420 specimens respectively.

For the C1water, C2water, C3water and C4water specimens, a very slight decrease in the UCS in the temperature range of 20°C to 350°C is shown. The UCS of both C1water150, C2water150, C3water150 and C4water150 specimens and C4water150, C1water350, C2water350, C3water350 and C4water350 represent respectively about 98% and about 90% of the UCS of C120, C220, C320 and C420.

Beyond a temperature of 350°C, a quasi-linear decreasing is noted. The residual UCS by C1water600, C2water600, C3water600 and C4water600 represent 30% and 31% of the UCS of C120 and C220, C320 and C420.

Figure 5 illustrates clearly the meaning of the relative change in residual UCS considering the 2 cooling regimes comparatively.

It can be seen that at a temperature of 150°C, the residual UCS of C1air150, C2air150, C3air150 and C4air150 is similar whereas that of C1water150, C2water150, C3water150 and C4water150 is much higher. Results are similar to the research conducted be précised this. Researchers agree that the dehydration of concrete during heating lead to the decrease in its residual UCS. At a temperature below 150°C, the free water evaporates, the concretes heated to 150°C and cooled in water are rehydrated and a large proportion of the evaporated free water is recovered. Between a temperature of 150°C and 350°C, the bound water contributes to the establishment of the internal pressures acting as a pre-stressed force that gives the strength peak. At a temperature of 350°C, the strength peak is observed for C3air350, the strength peak for concrete C3water350 being close to that of concrete C3air350. However, that of C1air350 and C4air350 remains well below that of C1water350 and C4water350. The reduction of the peak value in concretes C1air350, C2air350 and C4air350 is attributed to a reduction in the internal pressure during cooling in air. This is due to the phenomenon of transfer of part of the water vapour from the hot areas of the core of the test specimen to the cooled external areas. Beyond 350°C, a quasi-linear and important decrease in residual UCS is observed with a more pronounced gradient in the concretes subjected to thermal shocks in water.

The test specimens of C1water600, C2water600, C3water600, C4water600 and C1air600, C2air600, C3air600 and C4air600, heated at a temperature of 600°C, have the same residual mechanical behaviour. Many researchers [10, 11, 19 and 21] have given same observations. Probably, this is due to the fact that all the water in the concrete has disappeared at this temperature.

12. Conclusion

The following conclusions are given based on the results presented in this paper:

At room temperature, the C4 concrete has a UCS lower than C3 concrete. This decrease in UCS resistance is due probably to the poor adhesion between the PPF and cement paste.

The addition of PPF did not affect the shape of weight loss curves. The weight losses of C3 and C4 concretes are similar, and are more important than those ordinary C1 and C2 concretes.

Melting and evaporation of PPF create an additional porosity. The beneficial effect of PPF is due to the increase in porosity of C4 concrete which approximates that of ordinary C1 and C2 concrete. This porosity facilitates the circulation of the moisture flow, reducing the establishment of internal pressures described by some authors as a factor of thermal instability in the concrete.

Researchers agree that dehydration of the concrete during heating is the cause of mechanical characteristics decrease.

At a temperature of 150°C, the free water evaporates. Concretes, heated at this temperature and cooled in water, are rehydrated because the evaporated free water was recovered. Between 150°C and 350°C, the bound water contributes to the development of internal pressures shown by a peak of resistance.

At a temperature of 350°C, a peak of resistance was observed for the C3air350. This concrete cooled in air has a peak of resistance higher than those of C1, C2 and C4. This difference in the peak of resistance is attributed to the evolution in the internal pressure during the cooling.

The effects of high temperatures on the residual UCS of the concrete are lower when the concrete is subjected to thermal shock in air than in water.
The concrete specimens heated at a temperature of 600°C and subjected to different cooling treatments, have all the same UCS resistance. Probably, it is due to the fact that all the water in the concrete has disappeared at this temperature.

A beneficial effect of dredged sandy sediments on the physical and mechanical characteristics of concrete C2, both in room temperature and after the heating, is noticed. Its behaviour has been similar to that of concrete C1.

The DS can be substituted partially to the sand, especially fine sand, used in the manufacture of concrete. However, the supplementary experimentation will be necessary and will have to continue to confirm and validate these results achieved in laboratory.

Acknowledgements

The financial support of this study was provided by the research direction of the Ministry of Higher Education and Scientific Research in Algeria

References

[5] PIARC “Fire and Smoke Control in Road Tunnels”, PIARC Committee on Road Tunnels May 1999.
Tables

Table I. Chemical and mineralogical compositions of cement

<table>
<thead>
<tr>
<th>Components</th>
<th>SiO₂</th>
<th>CaO</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>SO₃</th>
<th>L.I.</th>
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</thead>
<tbody>
<tr>
<td>Ratio (%)</td>
<td>20.39</td>
<td>64.13</td>
<td>5.96</td>
<td>3.57</td>
<td>1.13</td>
<td>2.57</td>
<td>2.37</td>
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<tr>
<td>Mineral phases</td>
<td>C₃S*</td>
<td>C₂S*</td>
<td>C₃A*</td>
<td>C₂AF*</td>
<td>CaO free</td>
<td>Gypsum</td>
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<tr>
<td>Ratio (%)</td>
<td>60.04</td>
<td>12.54</td>
<td>9.25</td>
<td>11.02</td>
<td>0.35</td>
<td>4.00</td>
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</tr>
</tbody>
</table>

Note: LOI Loss on Ignition; * Notations used in cement industry.

Table II. Physical characteristics of quarry aggregates

<table>
<thead>
<tr>
<th>Physical Characteristics</th>
<th>Density (kg/m³)</th>
<th>Visual Sand Equivalent (%)</th>
<th>Fineness Modulus</th>
<th>Methylene Blue value (MB)</th>
<th>Absorption (%)</th>
<th>Los Angeles Ratio (%)</th>
<th>Micro Deval Ratio (%)</th>
<th>Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand 0/4</td>
<td>2640</td>
<td>79</td>
<td>2.25</td>
<td>1.28</td>
<td>1.10</td>
<td></td>
<td></td>
<td>Calcareous Siliceous</td>
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<tr>
<td>Gravel 3/8</td>
<td>2700</td>
<td>-</td>
<td>-</td>
<td>0.89</td>
<td>22</td>
<td>16</td>
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<td>Calcareous</td>
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<tr>
<td>Gravel 8/16</td>
<td>2700</td>
<td>-</td>
<td>-</td>
<td>0.90</td>
<td>24</td>
<td>16</td>
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<td>Calcareous</td>
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Table III. Physical characteristics and chemical components of dredged sediments

<table>
<thead>
<tr>
<th>Physical Characteristics</th>
<th>Measured value</th>
<th>Chemical Components (%)</th>
<th>Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content (%)</td>
<td>63.5</td>
<td>SiO₂</td>
<td>54.80</td>
</tr>
<tr>
<td>Blaine’s specific surface (m²/kg)</td>
<td>299</td>
<td>CaCO₃</td>
<td>19.30</td>
</tr>
<tr>
<td></td>
<td>2450</td>
<td>Al₂O₃</td>
<td>4.30</td>
</tr>
<tr>
<td></td>
<td>24.7</td>
<td>Fe₂O₃</td>
<td>0.44</td>
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<td></td>
<td>8.8</td>
<td>SO₃</td>
<td>0.00</td>
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<td></td>
<td></td>
<td>CO₂</td>
<td>15.62</td>
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<td></td>
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<td>H₂O</td>
<td>6.72</td>
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<tr>
<td>Methylene blue</td>
<td>4.8</td>
<td>Carbonates</td>
<td>40.5</td>
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<tr>
<td>Electrical conductivity (dS/m)</td>
<td>0.9</td>
<td>Organic matter</td>
<td>8.1</td>
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</table>

Table IV. Chemical and physical characteristics of siliceous fines

<table>
<thead>
<tr>
<th>Chemical Characteristics</th>
<th>Silica (SiO₂) (%)</th>
<th>Lime (CaO) (%)</th>
<th>Magnesia (MgO) (%)</th>
<th>Alumina (Al₂O₃) (%)</th>
<th>Iron Oxide (Fe₂O₃) (%)</th>
<th>Sulfates (SO₄) (%)</th>
<th>Loss on Ignition (%)</th>
<th>Carbonates (%)</th>
</tr>
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<tbody>
<tr>
<td>Values</td>
<td>91.21</td>
<td>2.51</td>
<td>0.00</td>
<td>0.11</td>
<td>0.73</td>
<td>0.00</td>
<td>2.53</td>
<td>4.54</td>
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<tr>
<td>Physical Characteristics</td>
<td>Density (kg/m³)</td>
<td>Type</td>
<td>Colour</td>
<td>Water Content</td>
<td>Blaine’s specific Surface (m²/kg)</td>
<td>Activity index</td>
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<tr>
<td>--------------------------</td>
<td>------------------</td>
<td>---------------</td>
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<td>--------------------</td>
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</table>
Table V. Composition data of concrete

<table>
<thead>
<tr>
<th>Values</th>
<th>Ferro Siliceous</th>
<th>(%)</th>
<th></th>
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<tbody>
<tr>
<td>2120</td>
<td>Grey</td>
<td>0.53</td>
<td>950</td>
<td>1.02</td>
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</table>

Table VI. Materials composition of concretes

<table>
<thead>
<tr>
<th>Components</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
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<tbody>
<tr>
<td>Cement (kg)</td>
<td>475</td>
<td>475</td>
<td>475</td>
<td>475</td>
</tr>
<tr>
<td>Gravels (kg) (3/8 + 8/16)</td>
<td>1115</td>
<td>1115</td>
<td>1115</td>
<td>1115</td>
</tr>
<tr>
<td>Quarry sand (kg)</td>
<td>656</td>
<td>492</td>
<td>492</td>
<td>492</td>
</tr>
<tr>
<td>Dredged sediments (kg)</td>
<td>0</td>
<td>164</td>
<td>164</td>
<td>164</td>
</tr>
<tr>
<td>Water (L)</td>
<td>214</td>
<td>212</td>
<td>190</td>
<td>190</td>
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<tr>
<td>Super-plasticizer (SP) (%)</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Silica Fume (SF) (%)</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Polypropylene fibres (PPF) (kg/m³)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
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Table VII. Number and type of cubic specimens of concretes

<table>
<thead>
<tr>
<th>Temperature &amp; Specimen Size</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C 4 series</td>
<td>4 series cooled in air</td>
<td>4 series cooled in air</td>
<td>4 series cooled in air</td>
<td>4 series cooled in water</td>
</tr>
<tr>
<td>20°C 1 series</td>
<td>1 series</td>
<td>1 series</td>
<td>1 series</td>
<td>1 series</td>
</tr>
</tbody>
</table>

Note: The Equivalent Binder is equal to the value of: \( k_{FS} \cdot SF + C \geq C_{min} \) wherein \( k_{SF} \) is the substitution modulus.
Factor of conformity in modular dynamic study of frame type constructions

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Abstract

The combined conducted analytical, numerical and experimental studies to specify the factor of conformity in modular dynamic tests of frame type constructions are presented in the current report. It is well known that experimental studies are carried out by creating scale models of the real systems based on linear, mass, inertia, elastic and other scales. Resulting characteristics, describing the dynamic behavior of the scale models, after multiplying by the corresponding modules provide information about the behavior of the real ones.

The factors of conformity to the own circular frequency and the amplitude of the forced vibrations, caused by kinematic sinusoidal interference, are analytically deduced in the report. The factors are applicable to one bay, one story frame with rigid external and internal links. The theory of the Deflection method of the Structural mechanics is used in the analytical determination of the coefficients. The numerical verification of the accuracy of the coefficients is realized through the appropriate software for dynamic analysis of structures, working based on the finite element method. Approximate experimental verification of the deduced dependencies is done through dynamic analysis of two models by Stand for modular dynamic tests of structures, subjected on seismic impacts. Developed methodology for determining the coefficients of conformity can be used for other class structures, including those with limited or infinite number of degrees of freedom.

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Keywords: scale dynamic model; numerical experiments; testbed experiments; factor of conformity.

1. Introduction

The dynamic study of the contemporary building structures is a complicated and complex task. The solution of the task is held in order analytical, numerical and finally experimental study. The analytical study is applicable to simpler structures or to separate their details. For more complex structures analytical part of the study is limited to preparatory work for the next stages. Numerical study is related to the decision of the analytical deduced mathematically records, describing the dynamics of the system. The holding of the numerical study requires the development of programs or simulation models by means of software packages for computational mathematics as Matlab, Maple, Mathematica. Many freedom of the research and practically unlimited possibilities for numerical dynamic analysis provide the new software packages based on FEM (SAP 2000, RSAP, Ansys, Comsol etc.). The third and final stage of the full dynamic study is the experimental. Various scale models of the real structures are created for conducting of the experimental research. The scale models are subjected to relevant impacts to determine their dynamic behavior. Information about the dynamic behavior of the real structures is obtained by processing of the characteristics, describing the dynamics of the scale models. This involves the use of respectively factors of conformity, giving connection between the characteristics of the both models.

A complex dynamic study of one bay, one story frame with rigid external and internal links is conducted in this report. The main part of the study is devoted to determining of the factor of conformity to the floor displacement, caused by sinusoidal kinematic impacts in the supporting nodes. The amplitude of the force undamped vibrations of the system is analyzed to determine the above mentioned factor. The value of the factor for such a simple system gives the range, in which the latter should be sought, in more complex systems and more complicated undeterminate impact. The simple character of the test system allows analytical, numerical and experimental solution of the problem.

Nomenclature

\[ m, m_1 \] mass of the storey of the real and the scale model
\[ EI, EI_1 \] stiffness coefficient of the column of the real and the scale model
\[ l, l_1 \] height of the column of the real and the scale model
\[ \omega, \omega_1 \] own circular frequency of the real and the scale model
\[ \theta \] force frequency
\[ \mu = \theta / \omega \] relative frequency
\[ A, A_1 \] amplitude of story vibrations of the real and the scale model
\[ \rho_l, \rho_m \] linear and mass factor
\[ \rho_{EI} \] stiffness factor
2. Analytical, numerical and experimental procedure

Two similar dynamic models are used for the conduct off combined determination of the factor of conformity. The models are shown in Fig. 1. As characteristics for the first (Fig. 1. (a)), can be used standard average statistical for such a frame values. The second is a scale model with random mass, stiffness and linear scales. The stiffness of the beam in both models is accepted for infinity. The axial distance between the columns is not fixed, because it does not influence on the dynamic behavior of the systems.

![Fig. 1. (a) A typical 2D frame; (b) Scale model of 2D frame.](image)

2.1. Analytical study

The analytical study is based on the theoretical formulations of the discipline of Structural Mechanics. $[k]$ form Deflection method is used in study of the dynamic behaviour of the systems. The sequence of application of the method is as follows. The moment diagram from a single displacement of the applied linear support is defined initially (Fig. 2. (a)). Next step is the determination of the same diagram from the amplitude of the kinematic effect on the supporting nodes (Fig. 2. (b)). As a kinematic effect is accepted sinusoidal vibration of the supporting nodes with forced frequency in the range of 0.75-0.85 from the base one.

The diagrams, caused by the single displacement and amplitude value of the forced sinusoidal effects for the scale models of Fig. 1. (b) are with the same shape as those of Fig. 2. The values of the last depends on the characteristics of scale models.

The next step is determination of the reactions of the applied linear support. The reaction from a single displacement of the linear support is used for determination of the own circular frequency of the system. The reaction from the amplitude value of the sinusoidal impact is used to determine the displacement from that impact.

$$k_{ff} = \frac{2 * I2 * EI}{l^3}$$

Fig. 2. (a) Moment diagram from $v_1=1$; (b) Moment diagram from the amplitude value of the sinusoidal impact.

The reaction from a single displacement (Fig. 2. (a)) is defined as the amount from the shear forces in columns and has the form

$$k_{ff} = \frac{2 * I2 * EI}{l^3}$$

The own frequency of vibration of the model from the same figure is calculated by the formula for frequency of the vibrating system with 1 degree of freedom (DOF).
\[ \omega = \sqrt{\frac{k_{ij}}{m}} = \sqrt{\frac{24 \cdot EI}{I^* \cdot m}} \]  

(2)

The own frequency of vibration of the scale model can be calculated by a similar formula.

\[ \omega_i = \sqrt{\frac{24 \cdot EI_i}{I_i^* \cdot m_i}} \]  

(3)

The module (factor of conformity) of the own frequencies is determined as the ratio of the last.

\[ \rho_o = \frac{\omega}{\omega_i} = \frac{24 \cdot EI \cdot I_i^* \cdot m_i}{I^* \cdot m \cdot 24 \cdot EI} = \frac{\rho_{ij}}{\rho_{i} \cdot \rho_{m}} \]  

(4)

The reaction from the amplitude value of the sinusoidal impact in supporting nodes is proportional of the reaction from a single displacement.

\[ K_{\xi_0} = -\frac{2 \cdot 12 \cdot EI}{l^*} \cdot \xi_0 = -k_{ij} \cdot \xi_0 = -\omega^2 \cdot m \cdot \xi_0 \]  

(5)

The displacement of the floor level from this impact will be determined by the condition of dynamic equilibrium in direction of the displacement.

\[ (k_{ij} - \theta^2 \cdot m) \cdot v_{\xi_0} + K_{\xi_0} = 0 \]  

(6)

\[ (\omega^2 \cdot m - \theta^2 \cdot m) \cdot v_{\xi_0} - \omega^2 \cdot m \cdot \xi_0 = 0 \]  

(7)

\[ v_{\xi_0} = \frac{\omega^2 \cdot m}{(\omega^2 - \theta^2) \cdot m} \cdot \xi_0 = \frac{1}{(1 - \mu^2)} \cdot \xi_0 \]  

(8)

From the theory of the free undamped vibrations of a system with 1 DOF is known, that the law of motion will be the sum of the solutions of the homogeneous differential equation and private integral. The amplitude of the private integral in this type of vibration is equal to the displacement of the floor level from amplitude value of the impact.

\[ v = C_1 \cdot \cos(\omega \cdot t) + C_2 \cdot \sin(\omega \cdot t) + v_{\xi_0} \cdot \sin(\theta \cdot t) \]  

(9)

At zero initial conditions the coefficient \( C_1 \) is zero and the coefficient \( C_2 \) will have the type

\[ C_2 = \frac{\theta}{\omega} \cdot v_{\xi_0} = -\mu \cdot v_{\xi_0} \]  

(10)

The final form of the law of motion will be

\[ v = -\mu \cdot v_{\xi_0} \sin(\omega \cdot t) + v_{\xi_0} \cdot \sin(\theta \cdot t) \]  

(11)
A short analysis of the vibrations, described by above law shows the following. The amplitude of the total vibrations will vary within the range $v_{max} - v_{min}$. The maximum value of the total amplitude will be in simultaneously close to the unit value and equal sign of the amplitudes of the two component sine functions. When forced frequency of the impact is less than the own frequency of the system, amplitude will look like

$$A = v_{max} = \mu \ast v_{z0} + \nu_{z0} = v_{z0} \ast (l + \mu) = \frac{l}{l - \mu} \ast \xi_{f0} \ast (l + \mu) = \frac{\xi_{f0}}{l - \mu}$$

(12)

The increase of the amplitude to a maximum value will occur twice for the time for which vibration by their own sinewave become one more than the vibration under the forced. The period of change of the amplitude can be found using the formula

$$T_v = \frac{2 \ast \pi}{\omega - \theta}$$

(13)

The general appearance of the graph of the summary vibrations of the system can be viewed on Fig. 3.

Finally, it can be found the factor of conformity for maximum amplitude in two large-scale model

$$\rho_v = \frac{A}{A_j} = \frac{v_{max}}{v_{j,max}} = \frac{\xi_{f0}}{\xi_{j0}} \ast \frac{l - \mu_j}{l - \mu}$$

(14)

Usually the ratio of the amplitudes of the forced kinematic impact is equal to the linear module. Then the formula (14) will get the type

$$\rho_v = \frac{l - \mu_j}{l - \mu}$$

(15)

2.2. Numerical studies

The numerical study is realized in two areas. The first is the area of software system Matlab / Simulink. Program for visualization of the described by formula (11) law of forced vibrations has been developed in Matlab environment. The vibrations in standard and scale model of the frame of Fig. 1 are visualized by the program. The maximum amplitudes in the both vibrations are determined by the graphs. The ratio of the maximum amplitude gives the factor of conformity for the floor displacements.

The factor of conformity is compared with that, obtained by formula (14). It can be used formula (15), if the ratio of amplitudes of kinematics impact is equal to the linear module.

Graphs of the vibrations in random data for the both models are shown in Fig. 4. The data, at the which the graphs are derived, are given below.

![Graph of total vibration of the system](image)

The factor of conformity, obtained as ratio of the maximum amplitudes of the force vibrations, is 2.523. The factor of conformity, analytically derived on the base of formula (15), is 2.5. There are quite close values, which numerically verify the correctness of the analytical procedure.

Numerical analysis is also realized in the area of the software system Ansys. A series of numerical experiments with real and scale models were conducted. The value of the factor of conformity varies in the range of 2.8% of the theoretical coefficient, computed by the formulas (14) или (15). Due to the limited format of the report, results from these studies are not shown.

![Graph of total vibration of the scale model](image)
2.3. Experimental study

Stand for modular dynamic tests of frame type structures [6] is used for experimental study. The stand is a part of the facilities of the Laboratory for numerical and experimental dynamic modeling at the UACEG, Sofia, Bulgaria (www.dlab-uacg-bg.eu).

Two models, with scale linear and mass characteristics, are tested on the stand. Photos of the two models are shown in Fig. 5. The characteristics of both models are given on the right of the photos.

![Figure 5](image1)

Fig. 5. (a) Experimental study of standard model; (b) Experimental study of scale model.

Based on the shown in the figure characteristics, the natural frequencies of the both models are derived by formulas (2) and (3). Then, through the system for controlling the movement of the stand, the models are driven by the specified sinusoidal impact. The amplitudes of the impact are selected so, that their ratio to be equal to the linear scale of the models, which is 1.275. The forced frequencies are selected so, that the relative frequency to be equal respectively to 0.8 for the first and 0.75 for the second model. The movement of the floor surface is recorded by a special system [5], then the results are processed in the area of Matlab program. The results from the movement of the two models are visualized in Fig. 6.

![Figure 6](image2)

Fig. 6. (a) Graph of story vibration of the model 1; (b) Graph of story vibration of the scale model.

The factor of conformity, with respect to the maximum displacement, obtained as ratio of the first to the second gives 1.468. By formula (15) the same factor is obtained 1.594. The difference of about 9% is within the range of permissible under experimental studies.

3. Discussions

The close results in terms of the factor of conformity, from the conducted combined dynamic analysis of plane one bay, one story frames, verify the correctness of the methodology. It should be borne in mind, that the results are most accurate at the relative forced frequency in the range 0.65-0.9. In this interval of variation of the relative frequency, the graph indicates several internal vibrations within the period calculated in formula (13). At closer values of the own and the forced frequency approaches the resonance mode, which is dangerous, especially in experimental tests. At a relative frequency less than 0.65 within the period $T_0$, it is observed a small number of vibrations, it being possible the maximum amplitude of the vibration to be significantly different from that, calculated by the formula (12).

In drawing up the scale models, most important is the linear scale. The latter should not be more than 4-5, because in the formula for frequency module is of a third degree. For larger values of the linear scale will be obtained systems with different in order natural frequencies, which will result in a large difference in the results with respect to the displacements.

In models with larger linear scales, can vary by stiffness and mass scale, so that the factor of conformity to the own frequencies to be in the range 1.5 – 2.5.
4. Conclusion

The proposed combined methodology for determining a factor of conformity for the displacements of the story plates of a standard and the scale models, is an open system and can be changed. It can be applied in plane frames with 1-3 joint internal or supporting links. With such a change would be modified formulas (2) and (3) for the own frequencies, but will not change the next formulas, describing the factors of conformity, including and that for the own frequency.

The methodology, especially in its numerical and experimental section, can be applied to study the dynamic behavior of multi storey or multi bay frames. The recommendations, given above for the range of variability of the relative forced frequency, should refer to the ratio of forced frequency to the first own frequency of the plane systems.

With respect to the impacts, the methodology assumes easily change of the deterministic with undeterministic interferences, for example recorded by vibrometer seismic interferences. The average amplitude of the impacts should be the average amplitude of the actual impact, multiplied by the linear scale of the numerical or the experimental models.

Acknowledgements

The report's authors express their gratitude to the management of the Laboratory for Numerical and Experimental Dynamic Modeling at the UACEG, Sofia, Bulgaria for the provision of hardware, software and experimental base [1], [2], [6].

References

Modular approach in creating the matrix equations, describing the free vibrations of discrete plane systems

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Abstract

A large part of present engineering structures are complex mechanical systems with a large number of degrees of freedom (DOF). Matrix mechanics and mathematical software for engineering calculations are basic tools in studying the dynamic behaviour of such systems. An inductive scientific approach to study the dynamic behavior of complex plane systems are available in the research of this report. The conception of the approach is to examine the modules from simple systems with 2 DOF, composed of bodies performing simple motions (translation, rotation), interconnected by joints and elastic-viscous connections. The dynamic and mathematical models are constructed so, to be easily include into the models of more complex systems, composed of such simple modules. The inertial, elastic, dissipative matrices of the simple modules are composed in a form, that allows easy to form the matrix of the complex systems. The systems are open and can be supplemented with other bodies of the same kind, related to increasing the number of generalized coordinates and respectively the size of modular matrices in matrix equations. The matrices in the matrix differential equations, describing the motion of the systems (inertial, elastic, dissipative, etc.), are sparse matrices derived from the superimposition of modular matrices with a concentration of non-zero elements around the main diagonal. The lasts are very similar to the matrices of stiffness, in static and dynamic analysis of continuous systems with FEM, at an appropriate choice of the numbering of the nodes.

Keywords: dynamic model; mathematical model; inertia matrix; elastic matrix; dissipative matrix.

4. Introduction

The mechanical systems, including the plane, studied in mechanics, mechatronics and others are complex systems with finite or infinite number of degrees of freedom (DOF). The mechanical and mathematical modeling of such systems is usually done by modern computer methods. The latter provide practically unlimited possibilities in terms of the number of degrees of freedom and the complexity of the systems. However, the study of systems with a large number of DOF in the absence of enough experience, is quite a difficult task. A necessary condition for success is the researcher to have experience with simple, manageable, with two-three DOF systems, that allow even analytical solution. Moreover, the complex mechanical systems are often composed of simple modules with few (or even one) DOF, connected via additional links in the complex system.

Research in the present report are a part of a global research project. The purpose of the work on the project is to expand the knowledge in the theory of vibration of discrete plane systems. Modular dynamic, mathematical and computer models are created for systems with two bodies, performing simple movements - translation and rotation. With the models can be studied each of the main types of vibrations - free and forced, damped and undamped. After that the models of the complex matrix are obtained by the superposition of the modular models. The analytical and numerical studies in the report are the first stage of the work on this project, developed in inductive direction. Only undamped free vibrations of plane discrete system are considered at the start. With respect to the elements of the matrix differential equation, only the operations of formation of inertia (mass) and elastic matrix are treated.

Nomenclature

$m_i, l_i$ mass and length of the elements of the discrete system

$k_{ij}$ spring stiffness of the elastic links

$m_{ij}$ modular inertia (mass) matrix

$c_{ij}$ modular elastic matrix

$M$ complex inertia (mass) matrix

$C$ complex elastic matrix

5. Modular approach in creating the complex matrices

The modular approach is applied to a class discrete plane systems, composed of bodies performing simple vibrations. The movement of the translational vibrating bodies is constrained by internal and external linear elastic links. The movement of the rotational vibrating bodies is constrained by angular elastic links. The external and internal forces of friction in the system are neglected.
The plane system performs small free undamped vibrations around the position of stable equilibrium. The latter corresponds to the undeformed springs, and a vertical position of the rotating bodies. An approximate kind of a random discrete system by the mentioned class is shown in Fig. 1.

![Fig. 1. A typical 2D discrete system.](image)

The number of DOF of the system is equal to the number of the bodies. As generalized coordinates, describing the motion of the system, are selected the displacements of the translational moving bodies, and the relative rotation of the rotating bodies. The beginning of local coordinates is in the said position of stable equilibrium.

The differential equations, describing the vibrations of the system, have the following matrix form

\[
[M]_{nxn} \cdot \{q\}_{nx1} + [C]_{nxn} \cdot \{\dot{q}\}_{nx1} + [K]_{nxn} \cdot \{q\}_{nx1} = 0
\]  

The system can be divided into units of two bodies with motion translation - translation and translation - rotation. Between the couples of bodies, performing simple movements has elastic connection supporting the vibrations. The idea of the considered approach is to define modular matrices of these mass elastic couples.

### 5.1. Couple type translation - translation

The dynamic model of the couple type translation - translation is shown on Fig. 2. (a). The model consists of two masses, performing co-linear horizontal translation. The vibrating character of the movement of the couple is due to the internal spring connecting the masses.

The matrix system of differential equations, describing the motion of the couple, has the same form as in equation 1. The difference is only in the dimension of matrices - in this case will be 2x2.

![Fig. 2. (a) Dynamic model of couple type translation - translation; (b) Dynamic model of couple type translation - rotation.](image)

The mass matrix has a diagonal form due to absence of inertial link between the two generalized coordinates.

\[
[m] = \begin{bmatrix} m_i & 0 \\ 0 & m_j \end{bmatrix}
\]  

The linking of the two masses with internal spring gives values in the elastic matrix and on the elements of the opposite diagonal.
\[
c_y = \begin{bmatrix} k_y & -k_y \\ -k_y & k_y \end{bmatrix}
\]  

(3)

5.2. Couple type translation - rotation

Little more detail will be drawn the modular matrices of the couple type translation-rotation. The elements of these matrices will be got from the records of kinetic and potential energy of the system.

The kinetic energy of the body, performing translation is the energy of a particle

\[
E_{k,i} = \frac{1}{2} \cdot m_i \cdot \dot{x}_i^2
\]

(4)

The rotating body perform a complex movement - translation along the first body and rotation around their common point. The velocity of its mass center S will be the vector sum of the velocity of the translation and velocity of the rotation. The square of the magnitude of this velocity can be determined by the known variety of the cosine theorem.

\[
v_S^2 = v_i^2 + \omega_j^2 \cdot l_j^2 + 2 \cdot v_i \cdot \omega_j \cdot \cos(\varphi_j) = v_i^2 + \omega_j^2 \cdot l_j^2 + 2 \cdot v_i \cdot \omega_j
\]

(5)

In formula (4) is taken in mind that for small vibrations \( \cos(\varphi) \approx 1 \).

The kinetic energy of the rotating body will be determined by Königs’s theorem.

\[
E_{k,i} = \frac{1}{2} \cdot m_j \cdot \dot{\varphi}_j^2 + \frac{1}{2} \cdot J_0 \cdot \dot{\varphi}_j^2 = \frac{1}{2} \cdot m_j \cdot \dot{\varphi}_j^2 + \frac{1}{2} \cdot \dot{\varphi}_j^2 + m_j \cdot \varphi_j \cdot \varphi_j
\]

(6)

The total kinetic energy of translational - rotational couple will be

\[
E_{k,i} = \frac{1}{2} \cdot (m_i + m_j) \cdot \dot{x}_i^2 + \frac{1}{2} \cdot m_j \cdot \dot{\varphi}_j^2 + m_j \cdot \dot{\varphi}_j
\]

(7)

It is well known, that the kinetic energy can be recorded in standard or matrix quadratic form in terms of generalized velocities.

\[
E_{k,i} = \frac{1}{2} \cdot m_{ij,11} \cdot \dot{\varphi}_j^2 + \frac{1}{2} \cdot m_{ij,22} \cdot \dot{\varphi}_j^2 + m_{ij,22} \cdot \dot{\varphi}_j \cdot \dot{\varphi}_j = \frac{1}{2} \cdot \dot{\varphi}_j \cdot \left[ \begin{array}{cc} m_{ij,11} & m_{ij,22} \\ m_{ij,21} & m_{ij,22} \end{array} \right] \cdot \dot{\varphi}_j
\]

(8)

After equalization of the right parts of the formulas (7) and (8) is obtained and the mass matrix of translational - rotational couple.

\[
m_y = \begin{bmatrix} m_i + m_j & m_j \cdot \frac{l}{2} \\ m_j \cdot \frac{l}{2} & J_0 \end{bmatrix}
\]

(9)

Members of the mass matrix in the opposite diagonal are monitored, due to the inertia connection between elements of this type of couple.

The potential energy of the couple is sum of the energy of the angular spring and energy of the rotating body.

\[
E_{p,i} = \frac{1}{2} \cdot k_y \cdot \varphi_j^2 + \frac{1}{2} \cdot m_j \cdot g \cdot \frac{l}{2} \cdot \varphi_j^2 = \frac{1}{2} \cdot k_y + m_j \cdot g \cdot \frac{l}{2} \cdot \varphi_j^2
\]

(10)

The potential energy can also be recorded in standard or matrix quadratic form in terms of generalized coordinates.
By comparing the elements, before the squares of the generalized coordinates in formulas (10) and (11) is obtained the elastic matrix of the couple.

\[
C_y = \begin{bmatrix}
0 & 0 \\
0 & k_y + m_y * g * \frac{1}{2}
\end{bmatrix}
\]  

(12)

The absence of external horizontal spring is the reason for the shape of the elastic matrix with only one nonzero element.

5.3. Creating of the complex matrices

In creation of the complex matrices should be followed the sequence of construction of the model. In certain areas of the systems is possible to have fixed supports that can be considered as a body with number 0. In the construction can be inserted and simpler modules to the existing system. The latter can be realized as a special case of one of the modules, described in 2.1 or 2.2, after certain corrections.

More common such simpler modules are the following:

- Addition of spring and translating body to translating body, built with previous module. This module can be considered as a special case of the translation module - translation (# 2.1) with zero mass of the first body.
- Elastic join addition of rotating body to body, built with previous module. This module can be considered as a special case of the module translation - rotation (# 2.2) with zero mass of the first body.
- Addition of spring between two translating body, built with previous module. This module can be considered as a special case of the module translation – translation (# 2.1) with zero masses of the connected bodies.
- Addition of spring between fixed point and body, built with previous module. This is the previous case as the first body is with number 0.

After creation of the modular matrices by formulas (2-12) is carried out a certain treatment of the latter. The processing is with a view to conveniently program insertion of model matrices into the complex. In the processing is taken into account and certain areas of the software system Matlab / Simulink.

It is drawn zero square matrix with dimension the difference between the numbers of second and first body plus 1. Then the elements of the square modular matrix replaces the angular elements of the zero matrix. This preliminary preparation has the following Matlab programming procedure, implemented for the elastic modular matrix for couples with elements i & j (i<j):

\[C_{ij} = \text{zeros}(j - i + 1);
C_{ij}(1,1) = ci(1,1); C_{ij}(1, j - i + 1) = ci(1,2); C_{ij}(j - i + 1,1) = ci(2,1); C_{ij}(j - i + 1, j - i + 1) = ci(2,2).\]  

(13)

Visually the processing of the modular matrix has a following form

\[
[C_y]_{2,2} \Rightarrow \bar{C}_y = \begin{bmatrix}
0 & 0 & \Lambda & 0 \\
0 & 0 & \Lambda & 0 \\
M & M & MM & MM \\
0 & 0 & \Lambda & 0 \\
0 & 0 & \Lambda & 0
\end{bmatrix}
\Rightarrow \bar{C}_y = \begin{bmatrix}
C_{y,11} & 0 & \Lambda & 0 & C_{y,12} \\
0 & 0 & \Lambda & 0 & 0 \\
M & M & M & M & M \\
0 & 0 & \Lambda & 0 & 0 \\
0 & 0 & \Lambda & 0 & 0
\end{bmatrix}
\]

(14)

For processed matrices is accepted the indexing \(\bar{C}_{ij}\), to stay mark \(C_y\) for the numbering of the elements in the complex matrix. Then it is proceed to the drawing of the complex matrix. Again firstly is compiled square zero matrix of dimension \((n+1)x(n+1)\), when \(n\) is the number of DOF of the complex system. Finally are superposed the matrices \(\bar{C}_{ij}\), same number as the couples than built the complex system. The superposition is performed using the following Matlab procedure.

\[C = \text{zeros}(n+1);
C(i + 1: j + 1, i + 1: j + 1) = C(i + 1: j + 1, i + 1: j + 1) + C_{ij};\]  

(15)
Finally, the first row and the first column of the matrix C are removed. The new matrix will have dimension nxn, and the numbers of the rows and the columns will correspond to the numbers of generalized coordinates.

\[
C(1,:) = []; C(:,1) = []; \tag{16}
\]

The processing and compilation of the complex mass matrix is made in a similar way.

6. An example of application of the approach

The proposed approach is applied to the system of three translational vibrating bodies Fig. 4. It is shown only the formation of the elastic matrix, because the mass matrix is a diagonal with the values of the elements equal to the mass of the bodies.

![Vibrating 2D system with 3 DOF.](image)

It can easily determine, that the system consists of couples type translation - translation with number equal of the springs in the system. The sequence of construction of the system is an arbitrary. A plan of the building could be as follows

\[
[p_{01}] + [p_{12}] + [p_{23}] + [p_{03}] + [p_{13}]
\]

In the above construction with \( p_q \) are numbered the couples of which is constructed the system. The indices correspond to the indices of the springs.

The composite modular matrix will be 5 with dimension 2x2.

\[
c_{03} = \begin{bmatrix} k_{03} & -k_{01} \\ -k_{01} & k_{01} \end{bmatrix}, c_{12} = \begin{bmatrix} k_{12} & -k_{12} \\ -k_{12} & k_{12} \end{bmatrix}, c_{23} = \begin{bmatrix} k_{23} & -k_{23} \\ -k_{23} & k_{23} \end{bmatrix}, c_{03} = \begin{bmatrix} k_{03} & -k_{03} \\ -k_{03} & k_{03} \end{bmatrix}, c_{13} = \begin{bmatrix} k_{13} & -k_{13} \\ -k_{13} & k_{13} \end{bmatrix}
\]

The treated matrix, according to formula (13) will also be 5.

\[
C_{03} = \begin{bmatrix} k_{03} & -k_{01} \\ -k_{01} & k_{11} \end{bmatrix}, C_{12} = \begin{bmatrix} k_{12} & -k_{12} \\ -k_{12} & k_{12} \end{bmatrix}, C_{23} = \begin{bmatrix} k_{23} & -k_{23} \\ -k_{23} & k_{23} \end{bmatrix}, C_{03} = \begin{bmatrix} k_{03} & 0 & -k_{03} \\ 0 & 0 & 0 \\ -k_{03} & 0 & k_{03} \end{bmatrix}, C_{13} = \begin{bmatrix} k_{13} & 0 & -k_{13} \\ 0 & 0 & 0 \\ -k_{13} & 0 & k_{13} \end{bmatrix}
\]

Finally is drawn the complex matrix first with dimension (n+1)x(n+1). After the removing of the first row and first column is obtained and the final elastic matrix with dimension nxn.

\[
[C]_{n+1,n+1} = \begin{bmatrix} k_{03} + k_{03} & -k_{03} & 0 & -k_{03} \\ -k_{03} & k_{03} + k_{12} + k_{13} & -k_{12} & -k_{13} \\ 0 & -k_{12} & k_{12} + k_{23} & -k_{23} \\ -k_{03} & -k_{13} & -k_{23} & k_{03} + k_{13} + k_{23} \end{bmatrix}, [C]_{nn} = \begin{bmatrix} k_{03} + k_{12} + k_{13} & -k_{12} & -k_{13} \\ -k_{12} & k_{12} + k_{23} & -k_{23} \\ -k_{13} & -k_{23} & k_{03} + k_{13} + k_{23} \end{bmatrix}
\]
7. Discussions

The developed analytical numerical procedure for creating of the complex matrices is very convenient for synthesis of the studied systems. To the greatest extent this is true in the elastic matrix, especially in a constant number of the bodies. Any addition or removal of internal or external elastic links easily can be realized by numerical procedure (13), (15), (16). The change of the stiffness in a certain spring also easily is reflected by repeating the same numerical procedure.

The order in the drawing of the elastic matrix can be used to compile the disipative matrix in equations of damped vibrations.

4. Conclusion

The proposed analytical and numerical methods very similar to the sequence of work in drawing up the matrix of stiffness in FEM. The bodies (masses) in this methodology correspond to nodes in FEM. Elastic links correspond to the bodies in FEM.

In the described method above, the separate bodies have 1 DOF and elastic links in the system restrict movement in one direction. The methodology is open to increasing the degrees of freedom of the moving bodies (up to 6) and the directions of the limitation of internal and external connections (up to 6). This will be associated with a increasing in times of the dimension of the matrices and is subject of future research.

Acknowledgements

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References

Experimental comparison of different injection timings in an HCCI engine fueled with n-heptane

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Faculty of Technology, Department of Automotive Engineering, Ankara, TURKEY
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Abstract

One of the most effective methods to control the combustion phasing of a homogeneous charged compression ignition (HCCI) engine is injection timing. Injection timing affects the homogeneity of the mixture, start of combustion and heat release rate. In this study, the effects of injection timing on in-cylinder pressure, heat release rate, pressure rise rate and combustion duration were investigated in early direct injection HCCI engine as experimentally. The experiments were performed at 6 different injection timings ranging between 20 øTDC and 270 øTDC using n-heptane as the fuel. Test results showed that maximum in-cylinder pressure increased and start of combustion was advanced when the injection timing was advanced. Maximum in-cylinder pressures of 4.7 bar at 2 øTDC and 3.4 bar at -9 øTDC were obtained at injection timings of 270 øTDC and 20 øTDC, respectively. Moreover, single stage HCCI combustion was observed and combustion duration increased when the fuel was injected towards to TDC. An advance in the injection timing resulted in an increase in maximum pressure rise rate (MPRR). MPRR of 1.1 bar/ºCA at 6 ºCA bTDC was obtained at an injection timing of 180 ºCA bTDC. Therefore, combustion phasing in HCCI engine was controlled by changing the injection timing and the knock limit was estimated.

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Keywords: HCCI; Combustion; Injection timing; Direct injection;

1. Introduction

Over the past two decades, research on HCCI engines has been a topic of interest in both academia and industries since it has the advantages of both Spark Ignition (SI) and Compression Ignition (CI) engines air/fuel mixture is delivered into the cylinder with relatively low pumping losses in the throttle valve and auto ignited simultaneously in the combustion chamber thereby resulting in an increase in the combustion efficiency. The heat transfer losses decrease due to the shorter combustion duration. Moreover, there was a substantial improvement in the thermal efficiency since the engine could be operated with higher compression ratios at leaner mixtures. There is a drastic decrease in Nitrogen oxides (NOx) and soot emissions due to these characteristics of HCCI engines [1-3]. Control of combustion phasing and combustion rate in HCCI engines are the current challenges faced which deter its application and implementation in commercial vehicles. Furthermore, chemical reactions govern the combustion process due to fuel properties and thermodynamic properties of the mixture. Therefore, issues of misfire and knock are observed at low and full load conditions, respectively. This limits the operating range of HCCI engines. Parameters such as pre-heating the intake air [4,5], variable compression ratio [6,7], variable valve timing [8,9], different valve lift mechanisms[10], exhaust gas recirculation (EGR) [11-13] and increasing boost pressure [14] are applied in order to control HCCI combustion. Many investigations have been performed on alternative fuels having different octane and cetane numbers [15-17]. However, the operating region of HCCI engines could not be improved, especially at high engine loads, because there is no direct control mechanism of combustion phasing. Injection timing is yet another parameter in order to control the start of combustion and combustion phasing. Injection timing has remarkable influence on obtaining homogeneous charge. Injection timing has a direct impact on the homogeneity of the mixture, vaporization of the fuel and start of auto-ignition [18-20]. Petit et al [21] studied the effect of injection timing on the heterogeneity of the mixture. Tests were performed with two different injection timings: early injection timing with 200 deg before TDC and late injection timing with 80 deg before TDC. Early injection timing produced a reasonably homogeneous mixture while late injection timing produced a stratified mixture. Therefore, the heterogeneity of the mixture could be varied by changing the injection timing. Turkcan et al. [18] investigated the effect of second injection timing on the combustion and emissions characteristics of a direct injection HCCI gasoline engine by using ethanol and methanol blended gasoline fuel. Five different fuels (gasoline, E10, E20, M10 and M20) were studied at the same energy input by them. The test results show that the combustion and emissions characteristics can be directly controlled and HCCI operating range can be extended by the second fuel injection timing. The maximum cylinder gas pressure and rate of heat release significantly decreased and the start of combustion delayed with the retarding of the second fuel injection. Standing et al. [22] investigated the effects of injection timing and negative valve overlap on auto-ignition in a single cylinder direct injection engine. They found that start of
combustion was advanced with negative valve overlap at leaner mixtures. Moreover, early fuel injection resulted in a very homogeneous mixture thereby causing the mixture to ignite early and faster burn rates.

In this study, the effects of injection timing on HCCI combustion characteristics were studied in a four stroke, four cylinder gasoline direct injection HCCI engine. Thus, the variations of in-cylinder pressure, heat release rate, normalized cumulative heat release rate, pressure rise rate, maximum pressure rise rate and combustion duration were investigated.

2. Experimental Setup and Procedures

All experiments were conducted at the Advanced Power System Research Center, Michigan Technological University. A 2.0 liter, 4 cylinder, four stroke, direct injection, GM Ecotec gasoline engine was converted to operate in HCCI mode. The test engine specifications are presented in Table 1. An external fuel pump and e-motor were used to provide high pressure fuel (up to 150 bar) for direct fuel injection. An air heater was fitted between throttle body and intake manifold to increase the intake air temperature. The engine load and speed were controlled by a 460 HP GE adjustable speed AC dynamometer.

Table 1. Engine Specifications

<table>
<thead>
<tr>
<th>Engine Specification</th>
<th>Value/Description</th>
</tr>
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<tbody>
<tr>
<td>Engine model</td>
<td>GM Ecotec LHU Gen I</td>
</tr>
<tr>
<td>Bore x Stroke [mm]</td>
<td>86 x 86</td>
</tr>
<tr>
<td>Cylinder number</td>
<td>4</td>
</tr>
<tr>
<td>Displacement volume [L]</td>
<td>2.0</td>
</tr>
<tr>
<td>Compression ratio [mm]</td>
<td>9.2:1</td>
</tr>
<tr>
<td>Connecting rod length [mm]</td>
<td>145.5</td>
</tr>
<tr>
<td>Max power [kW@6000 min-1]</td>
<td>270</td>
</tr>
<tr>
<td>Fuel injection system</td>
<td>Gasoline Direct Injection</td>
</tr>
<tr>
<td>Valve system</td>
<td>DOHC 4 Valves</td>
</tr>
</tbody>
</table>

In-cylinder pressures were measured by 115A04 model PCB piezo pressure transducers. The measured pressure data as voltage was amplified using 1104CA model DSP charge amplifier and then processed using ACAP combustion analysis system. An encoder with a resolution of one degree was used to obtain crank angle measurements. The Merriam MDT500 air flow measurement system was used to measure the intake air mass flow rate. Fuel mass flow rate was measured using the 1700 model Micro Motion flow meter. A schematic of the experimental engine setup is shown in Fig.1. HCCI engine was controlled by dSPACE MicroAutoBox and RapidPro units. A MATLAB Simulink model was developed for the engine management system that includes control of injectors, spark plugs, variable valve timing, throttle body, high pressure fuel pump and EGR valve. dSPACE units also measure lambda, crank angle, intake and exhaust cam positions, fuel rail pressure, throttle body position, and EGR valve position.

All experiments were performed at six different injection starting angle which are 270, 180, 90, 60, 30 and 20 bTDC crank angle degree using n-heptane as the fuel. All tests were conducted at constant engine speed, intake temperature, injection pressure and full load conditions. In addition, all tests were performed at constant injection duration. Table 2 shows the test conditions.

Table 2. Test conditions

<table>
<thead>
<tr>
<th>Test Parameters</th>
<th>Value/Description</th>
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</table>
### 3. Results and Discussion

Temperature and composition of the charge during the compression stroke has a predominant effect on HCCI combustion. In Low temperature combustion (LTC) regimes such as HCCI, the combustion characteristics are much different from other combustion modes. Control of HCCI combustion is one of the primary challenges. However recent studies have shown that injection timing could be commonly used in order to control HCCI combustion, since it directly impacts the homogeneity of the mixture, start of combustion and combustion process. So, the effects of injection timing on HCCI combustion must be investigated in detail for better understanding of the causalities. Figure 2 shows the variations of in-cylinder pressure at different SOI versus crank angle. Maximum in-cylinder pressure of 4733 kPa at 2° CA BTDC was obtained when the fuel was injected at 270° CA BTDC whereas it reduced to 3368 kPa at 20° CA when the fuel was injected 20° CA BTDC. It was seen that the maximum in-cylinder pressure increased and it was obtained earlier in case of early injection timing. Early fuel injection gives rise to higher homogeneity and better mixing of the charge mixture. Moreover, early injection gives sufficient time for the fuel to vaporize and also improves combustion stability [23,24]. In case of advancing injection timing, the increase of maximum in-cylinder pressure can be explained by the fact that all fuel energy is released at a small interval of crank angle with more homogeneous charge mixture. SOC is retarded and large part of combustion occurs in the expansion stroke when the fuel is injected towards the end of compression stroke. This results in a drop in the maximum in-cylinder pressure.

---

**Table 1**: Engine Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Speed [min⁻¹]</td>
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<tr>
<td>Injection Pressure [bar]</td>
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</tr>
<tr>
<td>Injection Starting Angle [°CA, bTDC]</td>
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<td>Fuel Type</td>
<td>n-heptane</td>
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<td>Intake Valve Open. Angle [°bTDC]</td>
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<tr>
<td>Exhaust. Valve Clos. Angle [°bTDC]</td>
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<td>Throttle Body Position [%]</td>
<td>100</td>
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<td>Intake Air Temperature [°C]</td>
<td>80</td>
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<tr>
<td>Lambda</td>
<td>1.8</td>
</tr>
</tbody>
</table>

---

Figure 2. The variations of in-cylinder pressure at different SOI versus crank angle

Figure 3 depicts the variations of heat release rate at different SOI versus crank angle. It was depicted from Figure 3 that two stage HCCI combustion was seen in case of early injection. If injection retarded towards the end of compression, it results in a single stage combustion. This can be attributed to the fact that low temperature reactions could not occur at late injection timings and charge mixture is not homogeneous enough. As the injection is advanced, maximum heat release rate is obtained earlier at limited range of crank angle. In contrast, maximum heat release rate is determined in expansion stroke at late injection timing. So, maximum heat release rate decreases. Advancing injection timing leads to obtain auto-ignition conditions earlier in combustion chamber.
Figure 3. The variations of heat release rate at different SOI versus crank angle

Figure 4 shows the variations of normalized cumulative heat release at different SOI versus crank angle. It was seen in Figure 4 that early fuel injection leads to earlier start of rising in cumulative heat release curve. The reason for this, early fuel injection brings about higher homogeneity and better mixing of air-fuel mixture in the cylinder. Also, the fuel has enough time for vaporization. As the start of injection timing is fixed towards to TDC, cumulative heat release rate gets closer to the TDC. Therefore, the combustion phasing starts an early crank angle and cumulative heat release curve was advanced. In HCCI engines, the crank angle which is corresponding to 50 % of cumulative heat release is very important for thermal efficiency. Especially, it should be nearly after TDC for higher thermal efficiency. If 50 % percentage of cumulative heat release is obtained earlier versus crank angle before TDC, thermal efficiency decreases due to negative work forced on piston. It can be seen in Figure 4 that, cumulative heat release decreases in 20-100 crank angle degree bTDC especially at early injection timings. This is because injected fuel into the cylinder at early crank angle vaporizes and absorbs a little amount of heat.

Figure 4. The variations of normalized cumulative heat release rate at different SOI versus crank angle.

Figure 5 shows the variations of combustion duration versus SOI. Combustion duration increased when SOI was retarded toward to TDC as seen in Figure 5, because there is no enough time to mix fuel molecules with oxygen molecules resulting in more heterogeneous charge mixture. So, combustion duration is prolonged at late injection timing values.

Figure 5 The variations of combustion duration versus SOI.

Knocking is also impacted by injection timing. Knocking occurs due to the instantaneous release of heat due to fuel energy at smaller range of crank angle. Hence, pressure rise rate increased at higher levels. This undesirable situation causes damage to the engine parts and limits the HCCI operating range. Figure 6 and 7 show the variation of pressure rise rate and maximum pressure
rise rate at different injection timing. Maximum pressure rise rate of 1091 kPa/°CA at 6°CA BTDC was obtained when SOI was fixed at 180°CA BTDC. Similarly, maximum pressure rise rate was obtained as 375 kPa/°CA at 7°CA BTDC when SOI was fixed at 20°CA BTDC. Maximum pressure rise rate was advanced and increased with the advance of injection timing. In addition, heat is released at smaller range of crank angle and more homogeneous charge mixture is obtained with the advance of injection timing. Pressure oscillations are observed at earlier injection timings as shown in Figure 2. Moreover, the temperature and pressure of mixture are lower with earlier injection timing. It means that the auto-ignition of cooler charge mixture is very difficult. Consequently, all charge mixture tends to participate auto-ignition chemical reactions spontaneously. It results in higher pressure rise ratio.

![Figure 6. The variations of pressure rise ratio at different SOI versus crank angle.](image)

![Figure 7. The variations of maximum pressure rise ratio depend on SOI.](image)

4. Conclusions

The aim of this study is to investigate the injection timing on combustion characteristics in an early injection HCCI engine fueled with n-heptane. For this purpose, the test engine was run at constant engine speed, injection pressure and lambda at different injection timing including 270, 180, 90, 60, 30, 20°CA bTDC. The test results showed that maximum in-cylinder pressure was obtained earlier when injection timing was altered from 20°CA to 270°CA bTDC. It was also seen that single stage HCCI combustion was observed and combustion duration increased as soon as injection timing is closed to TDC. The test results also showed that maximum pressure rise rate was obtained as 1091 kPa/°CA at 6°CA bTDC when the injection was performed 180°CA bTDC. This case shows the knocking tendency at earlier injection timing. It was seen that HCCI combustion could be controlled via injection timing and stable HCCI combustion occurred. It also causes to extend HCCI operating range at higher engine loads.

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References


High cycle fatigue properties laminate AA2519-Ti6Al4V

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Abstract

The paper presents preliminary results of high cycle fatigue properties, including fatigue cracking, layered laminate AA2519-Ti6Al4. The test material obtained was combined with the method of explosive bonding in direct configuration, as well as the intermediate layer using a AA1050 alloy. During the tests verified that the laminate will have a better properties combining the advantageous properties of titanium and aluminum. Loading applied during the tests was oscillating sinusoidal with the stress ratio R=0.1 and constant load frequency equal to 20 Hz. The tests were performed at five levels of stress amplitude dependent from shape of samples. Assumed as the criterion for the end was the number of cycles at specimen failure or when number of cycles was equal to 5 million repeats.

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Keywords: explosive welding, composite laminates, Al/Ti composites, highcycle fatigue ;

1. Introduction

Currently, there is a tendency to seek new materials characterized by, among others, favorable performance in relation to the materials used so far. These requirements are increasingly meet laminates, composites, including layered composites, the development of which involves the use of ever newer and more effective bonding techniques. One of the techniques for joining materials, complementing traditional methods, is a technique of explosive bonding, which allows you to combine materials with different mechanical properties, for example, metals do not weld and lightweight alloys. Explosive jointing allows the manufacture of laminates which are successfully used in the electro-mechanical industry. Usage of this type composites, as a construction material seem, in the light of the analyzed literature, very promising especially where the use of another type of connection is cumbersome, impossible or unprofitable. Materials used for mechanical structures are often subjected to varying loads periodically. Under these conditions, there may be a variety of damage to both the material-laminated components and their connection zones. A common example of this type of destruction of composites is the occurrence of exfoliation called delamination. Such cracks formed within the composite layer can significantly decrease the strength locally in particular tensile and flexural strength. The results of analysis of the literature indicate a fairly large group of publications on laminates Al-Ti. The majority of this work concerns the mechanical properties of the materials being bonded explosive, material and structure of the attachment zones. Much attention is paid to the formation and influence on the properties of laminates produced intermetallic precipitates such. Al3Ti [1-3]. Delamination formed in the middle of the wall thickness, dividing the laminate into two sub laminates can reduce the rate up to twice the bending strength of the total cross section. Particle formation Al3Ti entails the risk of creating a discontinuity of the material structure and the stress concentration due to a process of forming precipitates. They can act as notches that increase the probability of occurrence of cracks and delaminations [4-8]. A number of published studies devoted to heat treatment layered laminates and Al-Ti, with a view to causing the stress relaxation caused by the explosive bonding process. Heat treatment is described in [9] brought the expected results, but also caused a change in the microstructure of aluminum alloy. A heat treatment laminates Al-Ti including the oxidation of the composite and its impact on the physical properties of the material has been devoted to the work [10]. The analysis so far conducted research allows to assess the possibilities of application of laminates Al-Ti obtained by combining explosive only in the construction of statically loaded. In a few of them they address the issues of destruction of laminates as a result of cyclic loading [11-12]. They cause local hardening of the material, which significantly increases the resistance of the laminate on the dynamic effects of foreign bodies [13-16]. This Is, in the case of layered materials bonded by combining explosive issue undoubtedly important, allowing to characterize the laminate as a construction material that could be used for mechanical structures.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_f )</td>
<td>Number of cycles</td>
</tr>
<tr>
<td>( N )</td>
<td>Cycle number</td>
</tr>
<tr>
<td>( \sigma_a )</td>
<td>Strain amplitude</td>
</tr>
<tr>
<td>( \sigma'f )</td>
<td>Fatigue resistance coefficient</td>
</tr>
<tr>
<td>( E )</td>
<td>Young module</td>
</tr>
<tr>
<td>( R_m )</td>
<td>Maximum rupture resistance</td>
</tr>
</tbody>
</table>
Rp0.2  Ductility limit

2. Materials and experimental details

The tests involved a layered composite formed by explosion welding of base materials in the form of AA2519 aluminum alloy and Ti6Al4V titanium alloy with the intermediate layer of AA1050 alloy (Fig. 1).

![Layered composite](image)

Fig 1. Connection area of AA2519/Ti6Al4V with the intermediate layer of AA1050 alloy

Tensile properties and chemical composition of the alloys combine were obtained and are presented in Tables 1 and 2. The scope of the research included conducting tests on two batches of samples. The first of them is the resulting AA2519/ Ti6Al4V laminate, subjected only to straightening by additional rolling. The second batch is a layered material AA2519/Ti6Al4V, subjected to additional heat treatment.

<table>
<thead>
<tr>
<th>Chemical composition of AA2519 alloy.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition [wt%]</td>
</tr>
<tr>
<td>Si</td>
</tr>
<tr>
<td>0.06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chemical composition of Ti6Al4V alloy.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition [wt%]</td>
</tr>
<tr>
<td>O</td>
</tr>
<tr>
<td>&lt;0.20</td>
</tr>
</tbody>
</table>

A comparison of the fatigue properties AA2519/Ti6Al4V composite laminate before and after heat treatment is proposed in this research. Investigation was based on composite laminate produced through explosive welding from the following base materials: AA2519 aluminum alloy (AlCuMgMn+ZrSc) and Ti6Al4V titan alloy. The laminate is composed of base materials of 3 mm thickness (each). An additional 0.8 mm transition AA1050 alloy layer was required for the explosive welding process, more details on the constituent materials of the laminate contains. The tested composite after formation was annealed at 530–550 °C for 2 h, quenched in water at room temperature and then aged at 165 °C for 10 h to strengthen it. Before the start of fatigue tests the basic strength properties of the laminate obtained by explosive welding were checked [17-19]. The tensile tests were carried out for flat samples according to PN-EN ISO 6892-1:2010. The monotonic stress–strain curves that were obtained for AA2519/Ti6Al4V composite laminate before and after heat treatment shows Fig. 2.
These curves are examples of charts to verify the effect of heat treatment on the laminate. The most striking result to emerge from the data is that tensile strength increased from 570 MPa for basic material to about 620 MPa for laminate after the heat treatment. For AA2519/Ti6Al4V composite laminate, the yield stress was defined as the stress corresponding to 0.2% permanent strain. For this material parameter was also observed a positive effect of heat treatment, which improves the yield stress from 500 MPa to 580 MPa (Tab. 3).

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile strength (MPa)</th>
<th>Yield stress (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA2519/Ti6Al4V basic material</td>
<td>500</td>
<td>570</td>
<td>14</td>
</tr>
<tr>
<td>AA2519/Ti6Al4V after heat treatment</td>
<td>580</td>
<td>620</td>
<td>16</td>
</tr>
</tbody>
</table>

The last compared parameter shows the 2% increase in the minimum elongation after fracture of 14% to 16% for samples after heat treatment. In the remainder of this article will be carried out similar considerations the impact of heat treatment on fatigue properties of the tested laminate.

These investigations aim at comparing the high cycle fatigue behavior AA2519/Ti6Al4V composite laminate before and after heat treatment, based on experimental results from fatigue tests. On the basis of standards (ASTM E466, PN-74/H-04327, PN-EN 3987:2010) were developed shapes samples for testing fatigue life. The high cycle fatigue tests were performed using two types of specimens: flat with a central hole (Fig. 3a) and smooth - without hole (Fig. 3b). Research samples were cut from the sheet of laminate method of water jet cutting and then both shape series of 20 specimens have been treated.
The fatigue tests of samples of AA2519/Ti6Al4V laminate were conducted at room temperature on a computer-controlled 250 kN Instron 8802 closed-loop servo-hydraulic test machine. Loading applied during the tests was oscillating sinusoidal with the stress ratio $R = 0.1$ and constant load frequency equal to 20 Hz. The tests were performed at five levels of stress amplitude dependent from shape of samples. Assumed as the criterion for the end was the number of cycles at specimen failure or when number of cycles was equal to 5 million repeats.

3. Results and discussion

During high cycle fatigue testing, the test specimens made of AA2519/Ti6Al4V laminate were subjected to alternating loads until failure. The initial load levels were determined on the basis of static properties of the material selected for examination given in Tab. 1 and geometry of the specimens, which are shown in Fig. 3. Then the load was gradually reduced until the studies have reached the established limit of cycles to failure. From these tests, it was possible to determine $S$–$N$ curves that characterize the fatigue life behavior of a material test specimen. Effect of heat treatment on the fatigue properties examined laminate show graphs obtained for samples with a central hole (Fig. 4) and smooth samples (Fig. 5). Comparison chart fatigue life of material after heat treatment (diamonds) in relation to the base material (squares) presented in Fig. 4.. Regression lines obtained by least square method was carried out by the experimental points. A dashed line represents a base material and a solid line material after heat treatment. There are simple regression equations for these lines and the R-square coefficients on the chart. A detailed analysis of the Fig. 4 allows to determine that the effect of the heat treatment is visible the most at high stress. With maximum stress level $\sigma_{\text{max}} = 250$ MPa fatigue strength of the sample increased from $N_f = 2 \times 10^4$ to approximately $N_f = 5 \times 10^4$ cycles for samples after heat treatment. The number of cycles to failure for samples after heat treatment is bigger by about at 20 % in relation to basic material at the level of $\sigma_{\text{max}} = 250$ MPa. However, this effect is not observed for the maximum stress below 150 MPa. Confirmation of these findings is the intersection of regression lines at level $\sigma_{\text{max}} = 150$ MPa.
Fig. 4. Fatigue curves obtained for samples with a central hole

![Fatigue curve for central hole samples](image)

\[ \sigma_{\text{max}} = -64.92\log(N) + 1046.1 \]

\[ R^2 = 0.8738 \]

\[ \sigma_{\text{max}} = -54.18\log(N) + 899.01 \]

\[ R^2 = 0.9434 \]

Fig. 5. Fatigue curves obtained for smooth samples

Similar considerations for smooth samples presented in Fig. 5, therefore the marks in this figure are the same as for Fig. 4. It is interesting to note that in the case of this shape of samples positive impact the heat treatment is visible for the whole range limited durability. At the highest level of maximum stress of 350 MPa, the fatigue life of the samples after the heat treatment is even more than twice bigger in comparison to the base material. The number of cycles to failure for samples after heat treatment is bigger by about 30% in relation to basic material at the level of \( \sigma_{\text{max}} = 300 \) MPa and decreases to 20% at the level of \( \sigma_{\text{max}} = 250 \) MPa. Positive effect of heat treatment disappears at a level of 175 MPa. As might be expected the intersection of the regression line in this case was at the maximum stress level of 175 MPa.

Research and macro mikrofraktograficzne showed fatigue fracture surface character of the developed structure. Fatigue fracture surfaces of samples without cracking initiators shown in Fig. 6-7. Late sample topography observation performed with a scanning electron microscope showed the presence of connections in the border zone Ti6Al4V-AA1050 multiple foci of fracture characteristic, smooth surface (Fig. 6).
Fig. 6. Fracture surface of the sample before heat treatment

Electron-optical study indicate a much less developed fracture surface morphology of samples after heat treatment. Photography breakthrough in Fig. 7 Crack initiation in the elements after the heat treatment followed by the edges of the sample.

Fig. 7. Fracture surface of a sample after heat treatment

4. Summary

The study analyzed high cycle fatigue element model of laminate AA2519-AA1050-Ti6Al4V produced by explosive bonding. The study tested the impact of the applied heat treatment, and the notch in the form of a central bore. The results indicate the beneficial effect of the applied heat treatment, as the alloy AA2519. The stability samples showed an increase of the heat-treated samples, both notched and smooth samples. For samples with a hole increase in fatigue life were observed only in the tests above $\sigma_{\text{max}}=150$ MPa. The biggest, 30-percent increase in the durability of these samples occurred during testing at $\sigma_{\text{max}}=250$ MPa. He analysis of samples of smooth heat-treated samples showed an increase in stability after a heat treatment of 20-30 per cent of the range $\sigma_{\text{max}}=175-350$ MPa.

The results of studies of Electron surface fatigue fracture allowed to determine the location of sources of fatigue cracking, which in the case of samples without heat treatment were in the area of border merger Ti6Al4V-AA1050. Sources of cracking in the elements after the heat treatment were located within the edge of the samples.

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