Visualization of super-compressibility in supersonic spiral-twisted jets

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ABSTRACT

We have visualized first the super-compressibility and associated it phenomena in submerged under-expanded supersonic spiral-twisted gaseous jets during its flowing from the annular nozzle with a central cone. We have observed the regular unusual axial symmetric vortex structures of body rotation and chain structures of jets in argon, helium, nitrogen and air. The type of structure depends on geometry of nozzle and pressure in pre-chamber. Strong density gradient appears discretely in mentioned jets.

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0. Introduction

We discover the wave spiral structure in under-expanded vortex supersonic jet [1]. The self-focusing of shock wave in under-expanded supersonic gas flow was observed in [2–4] during flowing from the annular nozzle with a central cone. The design features of mentioned nozzle see in work [1]. In present work we have visualized first the super-compressibility and associated it phenomena in mentioned spiral-twisted gaseous jets during its flowing from the annular nozzle with a central cone (see Fig. 1). We have observed the regular unusual axial symmetric vortex structures of body rotation. At first in present work we discuss unusual chain structures of submerged under-expanded supersonic spiral-twisted gaseous jets during its flowing from the annular nozzle with a central cone in argon, helium, nitrogen and air. Here-with in present work we apply stereoscopic high speed shadow visualization (see Fig. 2). It permits us to detect unusual structures, when density gradient appears discretely in mentioned jets. Spatially periodic compressibility of the submerged gas jets leads to its dispersion or compression depending on position of central cone in pre-chamber. The unicorn horn type spiral-twisted gaseous jets were observed when conic central body was out of nozzle. The chain type spatially periodically coupled interacting jets were observed when conic central body was inside the nozzle. The unicorn horn type spiral-twisted gaseous jets curl up in line after 8–10 calibers. The chain type spatially periodically coupled jets dissipate after 3–4 calibers. Presented results confirm our previous investigations [1–4,6]. The estimation of discussed super-compressibility see in [6]. Vortex shock waves also are discussed earlier in our work [7].

1. Experimental part

1.1. Description of gas dynamic part

For the first time we have design a special annular nozzle with a cone central body as in [1] and in patent [5]. The nozzle is constructed with two cones (external and internal) with different angles. The inner cone might be disposed along the axis of the jet...
as in nozzle pre-chamber and outside it. We altered gas pressure and geometry of pre-chamber. Compressor provided filtered gas pressure equal to \( (0.3–0.6) \times 10^5 \) Pa. The pressure tuning in the pre-chamber was provided with nozzle effective diameter. When the gas is flowing out into the atmosphere it acquires a configuration of strong pronounced wave character of flow. And we can observe a supersonic jet with progressive flow compression. Fig. 1 shows annular nozzle with a conic central body and the angles of nozzle. Detailed construction of nozzle you can find in [1].

At first in present work we apply optical stereoscopic shadow arrangement (see Fig. 2) for visualization of discussed phenomena.

### 1.2. Description of stereoscopic shadow visualization

Density gradient in the flow was visualized by direct shadow method. As the source of light we used an excimer laser CL-7000 with radiation wavelength \( \lambda = 248 \) nm (ultraviolet range), duration of laser pulse less than 20 ns. Visualization was accomplished from two positions with difference of angles of \( 70^\circ \), \( \Delta t = 20 \) ns, energy of laser pulse \( E = 20–50 \) mJ. See Fig. 2.

Here are: 1 – beam expander (1:10); 2 – semitransparent mirror; 3 and 5 – mirrors; 4 – screen; 6 – photo camera and 7 – object of recording.

The stereoscopic shadow visualization method was provided. Laser beam passes through the quartz plate 2 with the angle 45\(^\circ\). Then it was directed to the object. Reflected beam passes to the object from the mirror 3. The angle of beam coincidence was 65 \( \pm \) 5\(^\circ\). The both shadow pictures were projected on the fluorescent paper screen. To even the brightness of two pictures, two different type of paper were used. Received fluorescent pictures were registered from the screen by the camera Canon 500D with objective with focus distance 90–200 mm. During the large size of jet detecting objective was moving away from the camera for 5–10 cm. Before the experiment the nozzle upper surface was regulated parallel to laser beams with 3\(^\circ\) accuracy. Body calibration was conducted with the cylindrical body of 10 mm diameter with cylindrical grooves on the lateral surface (Fig. 3). Calibration was conducted before every series of experiment what guarantees a high accuracy between two pictures in their height and scale. Shots scales in every pair coincide with accuracy not worse than 3%.

### 1.3. Experimental results

Figs. 3–5 show nozzle stereo record without supersonic jet. Using this construction with pressure \( (0.6–0.8) \times 10^5 \) Pa, the under-expanded supersonic jet with wave configuration appears.

### 1.4. Discussion of stereoscopic shaded flow visualization

Figs. 3–5 show calibration and position on central cone body inside and outside of nozzle. From Figs. 6, 7 we observe wave configuration with axis symmetry body rotation. We see also wave self-focusing in the knots. When the cone central body is fixed on another moving out of the nozzle the wave structure is stretched. When the conic central body is inside the nozzle than the wave structure length is decreasing and we see turbulent flow. We can observe an interesting fact in Fig. 6: we can see that the flow is visualized under the nozzle cut. In case if gradient of density presents pair of spirals we can observe spiral twisted, parallel straight and regular reacting shock wave configurations.
2. High speed supersonic flow recording

2.1. Experimental results

High speed supersonic flow recording was accomplished with straight shadow method. As source of light we have used single-mode laser LGN-315 with wave length $\lambda = 632$ nm. Registration was made with a high speed video camera IDT Motion Studio N3 with frequency of 6000 frames per second, exposition equal less than 6 micros. Shadow picture was constructed on a camera matrix with objective focus distance 750 mm. The main result of high speed visualization is the absence of rotation or transformation of the bounds primary structure in the flow. We observe only some fluctuations in bounds position, generally this structure is stationary in time. Nozzle rotation during the recording does not lead to any changes in shadow picture.

2.2. Discussion of results on laser shadow visualization

At first in present work (see Figs. 9–11) unusual chain structures of submerged under-expanded supersonic spiral-twisted gaseous jets in argon, helium, nitrogen and air was observed. Laser visualization in Fig. 9 allows observing twisted wave structure with length equal to 10–12 nozzle calibers. Flow as vortex cord is not dispersing in space, there is no turbulence. Here density gradient appears discretely in the jets.

Spatially periodic compressibility of the gas jets leads to its dispersion (see Figs. 7, 8) or compression (see Figs. 9–11) depending on position of central cone in pre-chamber. The unicorn horn type spiral-twisted gaseous jets were observed when conic central body was out of nozzle. The chain type spatially periodically coupled interacting jets were observed when conic central body was inside the nozzle. The unicorn horn type spiral-twisted gaseous jets curl up in line after 8–10 calibers. The chain type spatially periodically coupled jets dissipate after 3–4 calibers. Presented results confirm our previous investigations [1–4,6].

Fig. 10 shows a precise vertical curled wave structure of supersonic flow with axis symmetry body rotation. We see also wave energy accumulation in the knots. Wave period depends of the pressure inside the pre-chamber.

Fig. 11 shows a precise horizontal curled wave structure of supersonic flow with axis symmetry body rotation. We see also wave energy cumulation in the knots. Method of laser visualization allowed observe diffraction picture of supersonic wave. In the horizontal position the length of every curl is shorter in comparison with vertical position.

Our construction of nozzle and laser visualization methods allowed receives wave structure of under-expanded supersonic flow. We see manifestation of characteristics of gas as a wave. Mach shock waves and Mach reflections are not present in any of pictures of under-expanded supersonic flows.

Registered waves have spiral twisted, parallel straight and regular reacting configurations. We observe mutual interaction of waves with regular shock collapse and repulse in knots. Pulsation phenomenon is obvious. Classic Mach shock wave structure is absent in all experiments.
2.3. Shadow visualization with Toepler method

A peculiarity of the observed configuration of an underexpanded supersonic jet consists firstly in its helical character which reminds a weaved braid, and, secondly, in a spontaneous conic narrowing of the jets outcoming flow till some critical distance from the cut of the nozzle. In our experiments this distance was equal to 10 diameters of the nozzle cut approximately. For example, if the diameter of the nozzle cut was equal to 3 mm, then the self-constriction of jets was observed along the distance of 30 mm approximately. The jet with such helical configuration presents a new type of vortical tornado-like flows.

The point of wave formation in the gas flow is marked by macro-traces created in the inner part of solid metallic circular nozzle as an 8 deep lines "knife cutted"-like surface macro-defects.

Photo-records by means of the classical Toepler method reveal a formation of this helical configuration at gas pressure starting with rates of $0.4\,\times\,10^5$ Pa in prechamber. When the pressure increases, this configuration achieves a strong-pronounced character with the geometric parameters of the jet depending on the pressure and on the disposition of the inner parts and modules of pre-chamber relative to the nozzle cut. The nozzle and the jet were orientated in experiments along the vector of gravity. At Figs. 10 and 11 depending on changing geometry of pre-chamber the rotation of the jet corresponds to the right-handed screw (clockwise along an axis of the jet) and opposite – to the left-handed screw, with possibility to switch on and off the phenomenon of the Mach disk observed and a cellular structure exists on the main parts of Fig. 12.

2.4. Experimental results

Toepler visualization of bi-spiral-twisted under-expanded supersonic gas jets at different external parts dispositions of the central body see below (Figs. 12–14). Here are our previous results of providing of unicorn horn type of spiral-twisted gaseous jets.

2.5. Discussion of experimental results by Toepler method

As we see from Figs. 12–14, the different configurations of supersonic under-expanded flow was received due to the central cone body position changing without change of pressure. When the central cone body is out of the nozzle cut for 3–6 mm we ob-
serve a bi-spiral twisted under expanded supersonic gas flow. See more about these results in [1].

3. Conclusion

Our unique nozzle construction and three different methods of visualization permit us to detect unusual structures in submerged under-expanded supersonic jets. It leads to important conclusions:

- Gas behaves as wave spiral-twisted structure in supersonic jets.
- Density gradient appears discretely in mentioned jets.
- Chain type spatially periodically coupled jets were observed.
- Mach shock waves and Mach reflections have vortex structure.
- The type of structure depends on geometry of nozzle and pressure in pre-chamber.
- Spatially periodic super-compressibility provides unusual structures.

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