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EXCITATION OF SUBHARMONIC OSCILLATIONS IN AN AXISYMMETRIC FLOW WITH COHERENT STRUCTURES IN THE REGIME OF AEROACOUSTIC RESONANCE

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Conditions of origination of aeroacoustic resonance phenomena near an axisymmetric body in the form of a thick-walled tube in an air flow in a rectangular channel are studied experimentally. Dependences of the eigenfrequency of acoustic oscillations on the model length are determined. By studying the mechanism of origination of oscillations in the wake flow, it is shown that the process of generation of annular coherent structures in resonant regimes is characterized by evolution of nonlinearities, including a subharmonic packet. Possible methods of flow control are discussed.

Introduction. Approaches based on the notion of coherent structures (ordered formations in turbulent flows) are more and more extensively used in turbulence theory. New methods appear for flow description by expanding it into eigenfunctions. The advantage of these approaches is the possibility of deliberate control of turbulent flows, since ordered structures can serve as objects that can be manipulated to alter the flow as a whole. For the same reasons, the notion of coherent structures was used to study the laminar-turbulent transition, at least, its late stages. At the same time, there is a lack of papers wherein the knowledge of the fine structure of a turbulent flow is implemented in the form of flow control. This is related to the difficulties in identification of coherent structures and the necessity of finding effective methods of action on them and determining the contribution of changes in coherent structures to the total change in flow characteristics.

Aeroacoustic resonance is an example of a flow wherein the above-mentioned difficulties are observed but can be overcome, since coherent structures are clearly identified, it is possible to influence them effectively, and these actions have a significant effect on the flow.

Experimental and numerical studies of resonant phenomena in the flow around a periodic rake of plates in a rectangular channel, which are caused by unsteady shedding of the boundary layer from the trailing edges of the plates, were first described in [1, 2]. It was shown that the eigenoscillations in this case are purely acoustic and are not related to oscillations of the plates. The dependence of the amplitude of eigenoscillations on the spatial coordinates near one plate located in the plane of symmetry of the channel was studied in [3, 4]. The relationship between the resonant characteristics and the wake flow was considered in [5, 6]. Various aspects of mechanics of oscillations near the trailing edge were examined in [7–9]. It was shown that coherent structures manifested in the frequency spectrum of velocity oscillations arise in wake flows behind thick plates with rounded trailing edges. The frequency and amplitude of oscillations corresponding to these structures can be controlled by means of an external acoustic action. Sukhinin and Bardakhanov [10, 11] proposed a complete mathematical model for determining the acoustic eigenfrequencies of resonant volumes and compared the calculated frequencies with experimental data for the case of flat plates. At the same time,

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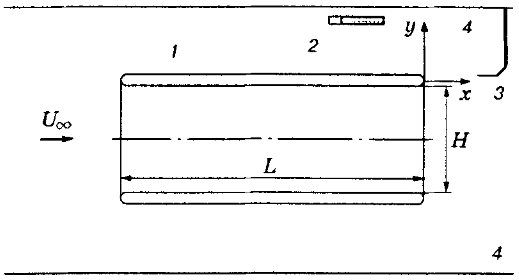

Fig. 1. Layout of the experiment: 1) model (axisymmetric tube); 2) microphone; 3) hot-wire probe; 4) test-section walls.

as far as the authors are aware, there were practically no systematic studies for an axisymmetric case (see [12, 13]). In particular, the existence of subharmonic disturbances in the near wake behind an axisymmetric model is noted in these papers.

The objective of the present work is to study the special features of origination of acoustic resonant oscillations in the flow with a bluff axisymmetric body and compare the results to the planar case. The flow structure in the separation region and in the wake is studied, and experimental data that may be used to control such a flow are presented.

Test Conditions. The measurements were performed at the Institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Sciences in an MT-324 subsonic closed-type wind tunnel with a closed test section 0.2 × 0.2 m and 0.8 m long. The layout of the experiment is shown in Fig. 1. The models were assembled from separate cylinders made as rings of transparent Plexiglas. Models of length $L = 100$, 200, 300, and 400 mm were used in the experiments. The inner diameter H of all models was equal to 84 mm. The wall thickness was $d = 8$ mm. The leading and trailing edges of the model were rounded with a radius equal to one half of the wall thickness. In some cases, the axisymmetric models were placed in a circular test section made as an insert into the square one. The axis of symmetry of the model mounted in the test section coincided with the axis of symmetry of the latter.

The mean velocity of the incoming flow was determined using a Pitot–Prandtl tube and a micromanometer. The measurements were performed within the range of free-stream velocities $U_\infty = 5$–47 m/sec. The streamwise components of the mean velocity U and the root-mean-square fluctuations of velocity u' at different points of the flow were measured using analog hot-wire equipment produced by the Dantec company and a probe with a gilded-tungsten wire of thickness of 6 μm and length of 1 mm. A block of the 55M01 type with a standard 55M10 bridge was used (the ratio of the bridge arms is 1 : 20 and the maximum frequency of the bridge is 200 kHz for a flow velocity around the probe of 100 m/sec); the output level of noise, in accordance with the producer's data, is 0.013% for a flow velocity of 10 m/sec. The hot-wire signal was fed through a GW Instruments MacADIOS-Adio analog-to-digital converter to a Macintosh personal computer where it was processed in digital form. The details of signal processing on a computer can be found in [10, 11]. The spectral analysis was performed in a narrow frequency band of 4 Hz.

The hot-wire anemometer was used to measure the velocity in the boundary layer and in the wake behind the model (at distances up to $x/d = 20$) and also to determine velocity fluctuations in the acoustic wave. The measurements in the boundary layers of the models showed that a turbulent boundary layer was formed on the major part of the models within the examined range of velocities. The measurements in the wake were performed in the vertical plane of symmetry passing through the model centerline. In what follows, the study is limited to the analysis of measurement results in the vicinity of the upper region of the trailing edge of the model, where the origin was located (Fig. 1). To control qualitatively the level of acoustic pressure and to analyze the spectral composition of the acoustic wave, a microphone was used, which was also a source of the reference signal for phase measurements. The microphone was not calibrated.

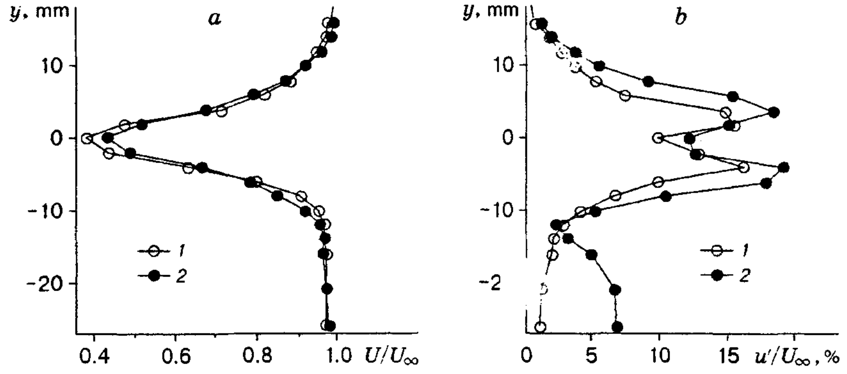

Fig. 2. Distributions of the mean velocity (a) and root-mean-square fluctuations of velocity (b) in the wake for $L = 400$ mm and $x/d = 1$: curves 1 and 2 refer to the nonresonant and resonant regimes, respectively.

In measuring the frequency of coherent structures in the wake, the hot-wire probe was positioned behind the trailing edge in an appropriate y position so that the ordered component of the spectrum was clearly observed in the signal on the oscillograph monitor. After a spectral analysis of the linearized hot-wire signal, we determined the oscillation frequencies f in the wake and the amplitudes of velocity fluctuations u'_f at these frequencies.

Integral Characteristics of the Flow over a Bluff Body and in the Wake. The experiments were conducted as follows. After wind-tunnel starting, the flow velocity in the test section gradually increased. When a certain value of the flow incoming onto the body was reached, the intensity of sound in the test section and in the room where the facility was located rapidly increased. The integral characteristics of the wake flow changed. Figure 2 shows the measured results for the mean velocity and root-mean-square fluctuations of velocity in the nonresonant and resonant regimes. Certain changes in the mean-velocity distribution are observed in the regime of intense emission of sound; in the region close to $y = 0$ (Fig. 2a), the flow velocity increases as compared to the nonresonant regime. The level of turbulence also increases (Fig. 2b). Similar changes in flow characteristics in the resonant regime were observed in studying the wake flow behind a planar bluff body [5]. It is also shown there that these changes are caused by the amplification of oscillations related to the existence of coherent structures in the flow.

The mean-velocity distribution obtained in the experiment is similar to the usual distribution in the wake behind a bluff body (for example, behind a plate). It should be noted that the velocity at the line corresponding to the middle of the edge gradually increases with increasing x, and, as in the planar case, the difference in the profiles of the mean velocity and root-mean-square fluctuations in the resonant and nonresonant regimes becomes undistinguished in the interval $x/d = 3$–5. At the same time, it was found that the spanwise distribution of the mean and fluctuating velocities, which is smooth in the beginning of the wake flow, is no longer smooth at certain distances from the trailing edge, though the number of realizations seems to be sufficient for averaging random oscillations in the profile. Similar measurements in the wake behind a planar model reveal a smooth change in the mean characteristics over the transverse coordinate y. In addition, as in the planar flow, two maximums in the distribution of the turbulence level in the beginning of the wake (Fig. 2b) rapidly merge into one, which is not observed in the wake behind flat plates. Since the flow behind the trailing edge of an axisymmetric model may be considered as a co-current jet, we can assume that these differences are caused by special features of the flow in a circular jet.

Effect of Flow Geometry on Acoustic Resonant Frequencies. The measurements were conducted in velocity ranges where resonant acoustic oscillations are excited in an axisymmetric case (similar to that made in [10, 11] for flat plates). However, in contrast to these works, it was not possible to perform detailed measurements of the distributions of the amplitude of acoustic oscillations near the model because of the specific features of the traversing gear. The main reason was the fact that, at least for a given ratio of

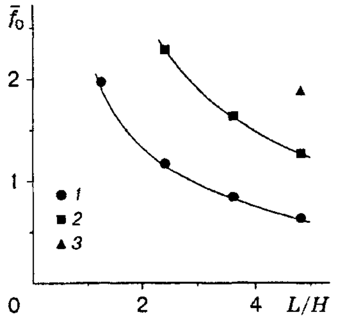

Fig. 3. Acoustic resonant frequencies versus the model length: curves 1–3 refer to the first, second, and third modes, respectively.

the model diameter and test-section dimensions, acoustic oscillations mainly arose inside the model and were much weakly expressed outside it (Fig. 2b). In the flow core, outside the boundary layer (at $y < -13$ mm), the amplitude of oscillations in the resonant regime was several times higher than in the nonresonant one. These oscillations are velocity oscillations in a standing acoustic wave inside the model. It should be noted that these oscillations were monochromatic in all resonant regimes both inside and outside the model, which was verified by the microphone.

The measurement results for resonant frequencies are plotted in Fig. 3. The frequencies registered by the hot-wire probe in sound-emission regimes were nondimensionalized in accordance with the relation $\bar{f}_0 = 2\pi f_0 H/c$, where f_0 is the frequency of sound measured in the experiment and c is the velocity of sound.

A qualitative comparison with the experimental and numerical data of [10, 11] obtained for planar models shows that the dependence of the frequency on the dimensionless length of the model for the planar and axisymmetric cases is described by similar curves. Probably, with an appropriate normalization, the acoustic resonant frequencies for axisymmetric and planar models may be described by identical dependences.

The results of experiments with a circular test section are qualitatively similar to those described above (the resonance was observed approximately for the same flow velocities and frequencies). The difference was the greater intensity of acoustic oscillations in experiments with some models. (The effect was estimated orally, since the construction of the traversing gear of the probe did not allow hot-wire measurements in the annular region between the test-section wall and the model, and positioning of the microphone in this region would lead to flow blockage.) We can assume that the annular region in the axisymmetric test section is similar to the internal region of the model, and the intensity of the standing acoustic waves in the annular region is commensurable with their intensity inside the model.

The measurements were performed with flat plates mounted in the square test section of the wind tunnel; these plates were used in [10, 11], and their thickness was equal to the thickness of the walls of axisymmetric models. It was found that the sound was louder in experiments with an axisymmetric model.

Mechanism of Generation of Eigenoscillations in the Wake and Subharmonic Disturbances. Comparison with the Planar Case. We consider special features of the source of oscillations in the wake, in particular, coherent structures. They are a source of weak acoustic oscillations undergoing resonant amplification when the frequency of the source coincides with the frequency of acoustic eigenoscillations of a particular volume [5].

In turn, the intense acoustic field affects the process of generation of coherent structures in the boundary-layer separation region; the significantly nonlinear character of interaction of vortical and acoustic oscillations is manifested. For example, the action of acoustic oscillations leads to "capturing" of the frequency of coherent structures [7–9]; in the regime of aeroacoustic resonance, the spectrum of oscillations in the wake flow contains higher harmonics [6].

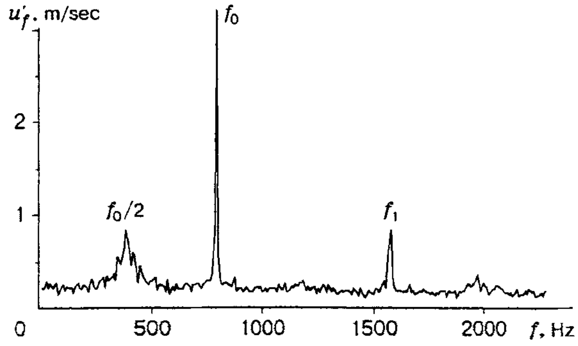

Fig. 4. Spectrum of velocity fluctuations in the wake behind the model in the resonant regime ($L = 400$ mm; second mode).

Figure 4 shows the spectrum of oscillations in the wake in the resonant regime. As in the planar case, there is the second harmonic f_1, apart from the first one f_0. The third harmonic was also observed. The frequency f_0 corresponds to the second resonant mode in Fig. 3 for the model 400 mm long, since in the resonant regime, because of the capturing, the frequency of the first harmonic in the wake becomes equal to the frequency of acoustic oscillations. A comparison with the planar case shows that the amplitudes of harmonics in experiments with an axisymmetric model are higher. However, in contrast to the planar case, there appeared a subharmonic $f_0/2$ in the axisymmetric wake. As is noted above, there were no frequencies except for the first one in the spectrum of sound, i.e., the higher harmonics and the subharmonic appeared under conditions of monochromaticity of acoustic oscillations. Though the width of the peaks corresponding to the first and higher harmonics was rather narrow, the region near the frequency $f_0/2$ was substantially wider. This is also valid for regions of multiple frequencies $3f_0/2$ and $5f_0/2$. Hence, a packet of disturbances is generated in these regions. The latter allows us to assume that an acoustic field of high intensity, which is the reason for generation of a subharmonic packet, only favors its identification at the background of small-scale turbulence under the present test conditions.

The measurements show that the positions of the characteristic points in the distributions of velocity fluctuations across the wake corresponding to the first and second harmonics and subharmonic do not coincide. A similar situation is observed for the planar case [6]. In particular, the distribution of velocity fluctuations corresponding to the first harmonic is similar to the distribution of the root-mean-square fluctuation of velocity (see Fig. 2). Significant asymmetry was observed in the distribution of fluctuations corresponding to the subharmonic: the amplitude in the upper maximum was significantly greater than in the lower one. Disturbances at the first harmonic in the resonant regime were observed in the turbulent wake up to the cross section $x/d = 20$. Subharmonic disturbances, which are observed in the wake, were hardly distinguished in the spectra at these distances because of the growth of background disturbances, though the amplitude at the frequency $f_0/2$ was of the same order as at $x/d = 1$. It should be also noted that disturbances with a frequency $f_0/4$ were sometimes observed in the flow.

For more exact measurements, we used averaging over an ensemble of realizations. The signal from the microphone was used as a reference one. Note that there was no significant increase in the amplitude of oscillations of the first harmonic in analyzing the signal, which was a result of summation of realization. This is apparently related to the fact that the signal-to-noise ratio in the examined region was rather high for the first harmonic. Though the signal from the microphone was subjected to low-frequency modulations caused by the noise in the flow, the use of this signal as a reference one allowed us to perform phase measurements.

Figure 5 shows the phase of oscillations of the first harmonic in the wake as a function of the streamwise coordinate. The measurements were performed in the resonant regime for the first mode. The phase of disturbances starts to change in the separation region, the wavelength λ equal to the distance at which the disturbance phase changes by 360° is 31 mm on the average, and the phase velocity of the disturbance

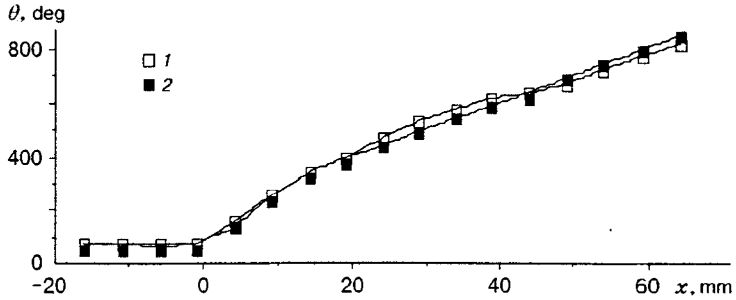

Fig. 5. Distribution of the phase of oscillations at a frequency f_0 along the streamwise coordinate in the wake ($L = 400$ mm; first mode): curves 1 and 2 refer to the phases in the upper and lower maximums, respectively.

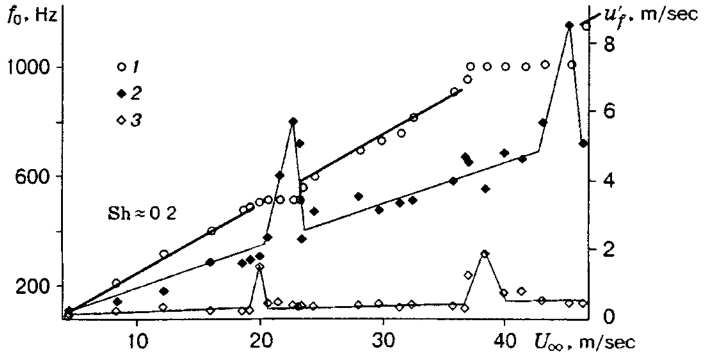

Fig. 6. The fundamental frequency of coherent structures in the wake behind the model (curve 1), the spectral amplitude at the fundamental frequency (curve 2), and the spectral amplitude at a half of the fundamental frequency (curve 3) as functions of the flow velocity ($L = 300$ mm).

u_θ determined from the relation $u_\theta = \lambda f_0/U_\infty$ is about 0.7 of the flow velocity $U_\infty = 18.5$ m/sec. The measurement results show that the disturbances propagate with an identical velocity in the outer and inner maxima over the transverse coordinate, since the curves almost coincide if one of them is parallel shifted by 180°, i.e., by the phase difference of oscillations in the maxima.

This phenomenon is observed for all radial positions of the probe. Therefore, though we did not perform visual studies, we can state that there are annular coherent structures in the wake. These structures originate in the separation region and propagate with a certain phase velocity. As in the planar case, the destruction of these structures in the region of the trailing edge by passive elements leads to the disappearance of the resonance. In this case, positioning of a wire ring on the trailing edge eliminates the resonance. Based on a rough estimate, at least half of the ring should be located in the separation region where the growth of the disturbance phases begins (Fig. 5). It should be noted that the phase velocity of disturbances for an axisymmetric model is close to the phase velocity for the planar case. A comparison with the data of [14, 15] shows that disturbances propagate with a phase velocity close to $0.7U_\infty$ both in a circular laminar jet and in the mixing layer.

Another situation was observed in the case of subharmonic oscillations. Higher harmonics were identified in the spectral analysis of the total realization, but the subharmonic could be revealed neither in the case of using the initial reference signal from the microphone nor in the case of the reference signal with a frequency $f_0/2$ generated by transforming the signal from the microphone by a frequency divider. Therefore, we can state that we could not observe synchronization of the packet of subharmonic disturbances with acoustic oscillations at the frequency f_0 excited in the resonant regime.

Resonant Ranges of Velocities and Regions of Existence of Nonlinear Oscillations. It is noted in [12, 13] that the character of variation of the intensity of the first harmonic and subharmonic in the resonant range is different. Figure 6 shows the dependence $f_0(U_\infty)$ obtained in the present work. As for the planar case (with flat plates used as models), there are regions of constant frequency with intense emission of sound at frequencies whose values are given in Fig. 3. In particular, for a model 300 mm long there are two such regions (within the examined range of flow velocities). However, in the planar case these regions are narrower for an identical length of the model. Probably, this is explained by the higher intensity of sound in the axisymmetric case. In addition, in contrast to the planar case, the frequency in the regime of aeroacoustic resonance could be either higher or lower than the frequency corresponding to the nonresonant regime at this flow velocity, which is clearly seen in the second "plateau." This frequency corresponds to the Strouhal number Sh = 0.2.

In the ranges of velocities at which there is no resonance, the spectrum of the signal in the wake contained one identified frequency. The corresponding points are well approximated by a straight line whose slope in these experiments is determined by the Strouhal number $\mathrm{Sh} = f_0 d/U_\infty \approx 0.2$. From the analysis of the dependence $u'_f(U_\infty)$ in Fig. 3, it follows that the resonance phenomenon significantly increases the amplitude of velocity fluctuations in the wake with a frequency f_0, and this frequency is maximum in the right parts of the "plateaus." Vice versa, disturbances at the subharmonic frequency are present in the left parts of the "plateaus." For the first harmonic, we speak about amplification of disturbances, and for the subharmonic, we see their origination. The subharmonic amplitude remained almost constant on both "plateaus" at this point of the flow.

It may be naturally assumed that, as in jets and mixing layers, vortices (or coherent structures) can merge in the examined flow (though it is significantly turbulent), which leads to the generation of subharmonic oscillations. As far as the authors are aware, an increase in intensity of acoustic oscillations in this case may intensify the process mentioned. Since it did not seem possible to control the resonance sound within the range of velocities of existence of the subharmonic packet, we used an active method of flow control: a loudspeaker as an additional source of sound, which allowed introduction of acoustic oscillations with varied amplitude and frequency into the flow.

The action of the loudspeaker was carried out at the frequency of the first harmonic, higher harmonics, and the subharmonic with different amplitudes of acoustic action. The realizations were summed using the signal at the frequency of the first harmonic or subharmonic as a reference signal. No effect of the external loudspeaker on the subharmonic amplitude was observed for various combinations of the frequency of action and the frequency of the reference signal. The shift of the central frequency of the subharmonic packet in the case of flow perturbation at frequencies close to this frequency was not observed either. Thus, in studies of both nonresonant [7, 9] and resonant [12] wake flow regimes behind a planar bluff body, the attempts at exciting a disturbance in the flow at the subharmonic frequency by an external source were not successful. These studies were performed because there are data that indicate that the flow structure can also be changed in the resonant ranges of velocities. For example, in the region of existence of a hysteresis, a source of sound, which is external for the aeroacoustic resonant contour, can exert a significant effect on the frequency spectrum of disturbances generated in the wake [16].

As is noted above, the subharmonic packet is generated only in the left (low-velocity) part of the "plateau." The intensity of sound at the resonant frequency reaches a maximum in the right side of the "plateau," where the subharmonic is not observed. Apparently, there are some synchronizing factors determined by the flow, which favor identification of the subharmonic packet in the resonant regime and which can hardly be affected by the comparatively weak action of the loudspeaker.

Since the subharmonic was observed on both "plateaus," i.e., in the case of existence of different acoustic modes, we can assume that the acoustic field distribution along the model does not affect the origination of the subharmonic packet. Hence, in the beginning of each resonant range of velocities, independent of the acoustic mode, some amplitude-phase relations or synchronization conditions are formed in the separation region, which favor identification of the packet of frequencies close to the subharmonic frequency.

The available results of measured subharmonic disturbances in the boundary layer and separated flows indicate that, for a subharmonic to appear, certain amplitude-phase relations should be satisfied. The reasons that favor generation of subharmonic disturbances in the wake behind an axisymmetric body in resonant regimes and methods of controlling these disturbances require additional studies.

Conclusions. 1. Experimental data were obtained on the influence of active and passive control actions on the regimes of sound amplification in a flow near thick-walled axisymmetric bluff bodies.

2. In all configurations examined, generation of coherent structures (apparently, annular ones) was observed in the separation region of the turbulent boundary layer near the trailing edge, where the interaction with sound occurs, which leads to the capturing of the wake frequency. By means of this process, the flow is self-tuned to the resonant regime. A modification of the separation region can lead to the violation of the synchronization process. As a consequence, acoustic oscillations are eliminated.

3. The dependences of the frequency on the model length were obtained for three eigenmodes. Variation of the model length can give rise to the resonant regime.

4. In contrast to previously obtained data for the planar case, the fundamental resonant frequency in the range of low velocities of the resonant interval was higher (and in the high-velocity region, lower) than the wake frequency determined by the Strouhal number for nonresonant regimes. For models of identical length, the resonant ranges of velocities are greater in the axisymmetric case than in the planar one.

5. In contrast to the planar case, the mechanism of nonlinear oscillations of the wake in the resonant regime is characterized by the fact that, apart from discrete components at the first harmonic and multiple to it, a packet of subharmonic oscillations is also generated; its central frequency is half of the frequency of the first harmonic. Dependences of the amplitude of the first harmonic and subharmonic on the flow velocity in the resonant ranges of velocities were obtained; the subharmonic component was observed only in low-velocity regions of resonant ranges.

6. The acoustic action of an additional source seems to have no effect on evolution of the subharmonic packet.

7. It may be assumed that the axisymmetric flow studied in the present work is characterized by stronger nonlinear effects than the planar flow.

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