ACOUSTIC SENSING OF HYDRODYNAMIC VORTEX FLOW

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We report the results of experiments of sound scattering by a vortex flow formed behind a grid of vertical cylinders placed in an air flow. The experiments were carried out in a low turbulence wind tunnel at a low Reynolds number. The vortex flow was formed behind a grid of 3-10 of hollow cylinders with the d=2 mm and length 30 mm. During the experiments we could change the gap between the cylinders g=L/d (where L is a distance between the cylinders surfaces) from 3 to 5. The experiments showed that at a certain value of g vortex flows behind different cylinders could synchronize and this effect could be easily detected by means of distant acoustic sensing. This result was also confirmed by means of direct measurements of velocity field of the vortex flow.

INTRODUCTION

Currently, laboratory remote acoustic diagnostics of vortical and temperature pulsations in air flows has been carried out for a number of well studied flows: the Karman vortex street behind a round cylinder [1-3], vortex rings [4], vortices behind a heated body [5], buoyant thermic [6], and heated jet [7]. These experiments have established the parameters of hydrodynamic flows, which can be determined by the characteristics of scattered sound. The experimental concept was that data obtained for flows with controlled parameters were to be compared to a calculation carried out within the models described by a small number of parameters: vortex circulation, vortex motion velocity, and quantity of heat transferred by vortices. The flows studied were actually laminar.

Laboratory acoustic diagnostics, making it possible to control all the parameters of flows, can be efficient in the simulation of acoustic sounding of the atmosphere and water reservoirs.

However, to compare laboratory and field experimental data on acoustic diagnostics of the atmosphere [8], scattering at more complex flows is to be studied.

The turbulence in the lower atmosphere can probably contain coherent components as well. Therefore, is seems important to study the potentials of acoustic diagnostics for turbulent flows containing large-scale ordered structures.

As a flow for laboratory acoustic diagnostics, we took a trace behind an array of round cylinders. A similar flow was visualized in [9] for laminar and turbulent flows. The wake was caused by a comb of 20 vertical cylinders immersed into a water flow with a soap film. The cylinder diameter was 0.12 cm, and the spacing between the neighboring cylinders was 0.3 cm.

The laminar flow was accompanied by systematic vortex separations, as well as Karman streets behind each cylinder. In the turbulent mode, the flow consists of a large number of randomly arranged vortices. Thus, changing the number of cylinders and the incoming flow velocity, one can change the flow types from a set of steady streets with high coherence to disordered ensembles of interacting vortices. Comparison of scattered sound parameters for various flows would allow one to trace the laminar-to-turbulent mode transition in the wake behind an array of cylinders by remote acoustic diagnostics. Furthermore, the study of sound scattering at various flow parameters (diameter of cylinder and spacing between them) offers better understanding of the results of field experiments on sound scattering by hydrodynamic and atmospheric turbulence.

1. EXPERIMENTS

The experiments were carried out in an air flow in a low-turbulence (the intensity of velocity turbulence pulsations in the windstream was less than 0.4 %) wind tunnel (Institute for Applied Physics) with an operating region of 30x30x120 cm. The experimental layout is shown in Fig. 1. We studied scattering of ultrasound at the frequency f = 122.1 kHz (λ = 2.7 mm) in a vortex street behind cylinders ($d=2$ mm) equidistantly spaced (L = 8-50 mm) (the distance varied depending on the experimental conditions) in the open operating region of the tunnel. The velocity of the incident windstream was varied to study the scattering of both laminar (the Reynolds number is $\mathrm{Re}=U_0 d/\nu$ =75, where U_0 is the windstream velocity and ν is air kinematic viscosity) and turbulent (Re = 490) flows. The number of cylinders was varied from one to ten. A piezoceramic sound source was placed behind a screen with a square hole (2x2 cm). The source was placed 65 cm apart from the street center for the Fraunhofer approximation to be satisfied $D_F \approx \Lambda^2/\lambda$ =30 cm, where Λ is the source size. The periodic vortical street emerged downstream behind the cylinders. To measure the ultrasound parameters, we used a high-frequency 4135 B&K microphone, whose signal was transferred into the range of 0-20 kHz by heterodyning. The microphone was placed 1.6m apart from the vortex street. Its position varied in the angular range from 45° to -45° with respect to the direction to the ultrasound source. The spectral characteristics of the scattered signal were measured using a computer. In particular, the directional patterns of scattered ultrasound were measured at various Reynolds numbers (75 and 490) for various numbers of cylinders.

2. EXPERIMENTAL RESULTS

As is known (see, for example, [1]), the amplitude of sound scattered in an infinitely long Karman vortex street to the first (Born) approximation of the scattering theory ($M \ll 1$, where M =

V/c is the Mach number) is a set of harmonics propagating symmetrically to the incident sound direction. The amplitude of each harmonic is proportional to the vortex circulation $G = \oint v\,dl$ in the street. The frequency of each harmonic is shifted with respect to the incident sound frequency f_0 by the value $\Delta f_n = nf_{sh}$, $(n = \pm 1, 2, ...,)$ multiple to the vortex separation (Strouhal) frequency f_{sh}. Each vortex scatters sound mainly forward; therefore, only +1 and -1 harmonics are typically observed in experiments.

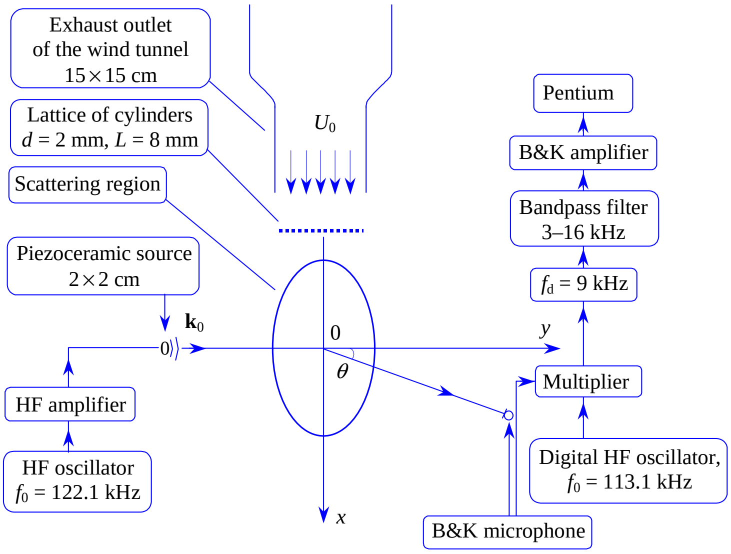

Fig.1 Experimental setup

Figure 2 shows the characteristic directional patterns of the harmonics observed for scattering at the Karman street behind 1,3, and 10 cylinders at Re = 75. The amplitudes and scattering angles into harmonics +1 and -1 exhibit asymmetry independently of the number of cylinders. Direct measurements of the velocity field in the street, carried out using heat-loss anemometers, showed that the street observed was turned by less than 3° with respect to the flow direction. Therefore, the angle k_0 between the incident sound and vortex directions differs from $\pi/2$.

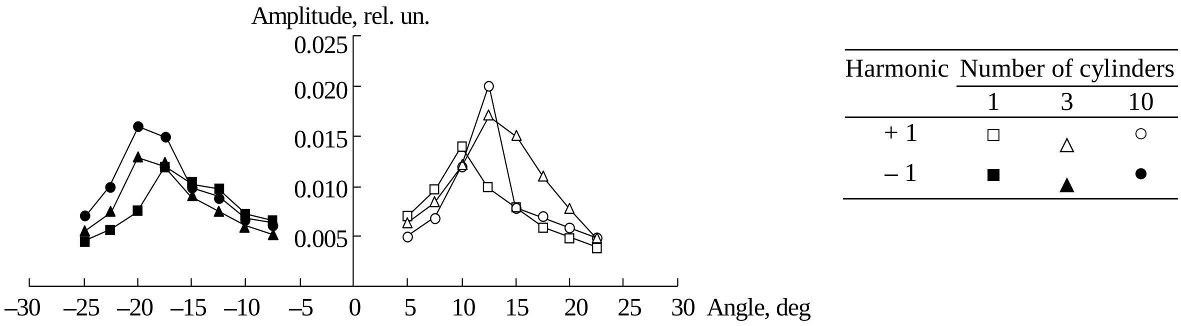

Fig.2 The distribution of the amplitudes of the 1-st harmonics of scattered sound for 1, 3, and 10 cylinders at Re=75

As the calculation [1] shows, this should cause the asymmetry detected in the experiment. Every harmonic has a characteristic width of the directional pattern, controlled by the following factor. The scattering volume has a finite size and a characteristic spectral width, since the velocity field in the street has a turbulent component in addition to the coherent one. In the experiment with three cylinders, the spacing L was the longest ($L = 4.5\ cm$) to minimize the impact of the interaction between the streets behind cylinders. With 10 cylinders, the spacing L between them was set as 1 cm. Comparison of the directional patterns of the harmonics (see Fig. 2), as well as the general view of the scattered signal spectra, allow the following conclusions. As expected, an increase in the number of cylinders causes an increase in the scattered signal amplitude. The ratio of the amplitudes of the signals scattered at one and three cylinders is $1/\sqrt{3}$. This means that the vortices from various cylinders are incoherent hence intensities, rather than amplitudes, are added. However, the ratio of the amplitudes in scattering at one and ten cylinders is much smaller than $\sqrt{10}$. The amplitudes of the scattered harmonics for Re = 75 are compared in Table 1.

A slower than $\sqrt{n}$ increase in the harmonics amplitude is caused by the interaction between the neighboring streets in the experiments with ten cylinders. This decreases the vortex circulation in the streets, hence decreases the scattered signal amplitude. For example, if the spacing between the cylinders is $5d$ (1 cm), the characteristic vortex circulation G in the streets decreases by about 40 % because of the interaction between the streets.

We now turn to the results of similar experiments for Re = 490 (turbulent flow). Comparing the experimental data, one can see that the transition to the turbulent flow causes (i) an increase of the scattering amplitude at the same number of cylinders (this increase is simply proportional to G and (ii) expansion of the directional pattern of each harmonic due to an increase in the turbulent component. Table 2 (similar to Table 1) lists the data for a turbulent flow. One can see that the effect related to the interaction between the streets (hence the vortex circulation decrease) is also retained for Re = 490.

Tab.1 Amplitude of harmonics scattered at the Karman street (Re = 75)

Number of cylinders	Amplitude of the + 1st harmonic, mV	Amplitude of the – 1st harmonic, mV	Dependence of $\sqrt{n}$
1	$3.9\cdot10^{-2}$	$3.7\cdot10^{-2}$	—
3	$5.6\cdot10^{-2}$	$4.9\cdot10^{-2}$	$5.32\cdot10^{-2}$
10	$6.4\cdot10^{-2}$	$6.2\cdot10^{-2}$	$12\cdot10^{-2}$

Tab.2 Amplitude of harmonics scattered in a turbulent flow (Re=490)

Number of cylinders	Amplitude of the + 1st harmonic, mV	Amplitude of the – 1st harmonic, mV	Dependence of $\sqrt{n}$
1	$4.3\cdot10^{-2}$	$4.2\cdot10^{-2}$	—
3	$5.7\cdot10^{-2}$	$5.4\cdot10^{-2}$	$5.95\cdot10^{-2}$
10	$9.0\cdot10^{-2}$	$8.2\cdot10^{-2}$	$13.43\cdot10^{-2}$

For better insight into the experimental data on sound scattering by the vortex wake, we directly measured velocity pulsations in the wake using a DISA heat-loss anemometer. Its position could be varied by an accompanying coordinate system. The downstream spacing between the heat-loss anemometer and the cylinder was selected to measure velocity pulsations in the range corresponding to a maximum intensity of the acoustic field. As is known, the heat-loss anemometer signal is related to the velocity modulus at the sensor point by the empirical dependence (King law) $U = A_1(T) + B_1 V^{0,45}$**,** where A is the coefficient depending on the sensor filament temperature, B is the empirical constant, and V is the velocity modulus at the sensor point. The sensor signal passed through a bandpass filter and then was computer-analyzed.

We measured the dependence of the amplitude of the first harmonic for pulsations of the velocity field corresponding to the Strouhal frequency (vortex separation frequency $f_s = U/l$, where U is the vortex velocity and l is the spatial period of the vortex street) on the sensor position across the wake. The vortex wake parameters (Reynolds number, number of cylinders, and spacing between them), at which the measurements were carried out, corresponded to those, at which the scattered sound spectra were measured.

The experimental data for the wake behind 1,3, and 10 cylinders at Re = 80 (laminar flow) are shown in Fig. 3. As the spacing between the cylinders decreases, the vortex streets begin to interact. Indeed, the pulsation amplitudes of the vortex wakes behind one and three cylinders almost coincide. The wake behind three cylinders exhibits the Karman vortex streets with identical pulsation amplitudes behind each of the three cylinders. In a wake behind 10 cylinders arranged close together, the pulsation amplitude is lowered at maxima (from 0.135 to 0.11 mV), and the number of streets decreases. Each street is to correspond to two pulsation amplitude maxima corresponding to chains of vortices with positive (+ G) and negative (- G) circulations. However, only 11 maxima are observed instead of 20 (see Fig. 3, bottom). Thus, the interaction between various streets behind the array of cylinders results in coalescence of the streets, in addition to the circulation G decrease. In our experiment, a single street emerges behind each pair of cylinders.

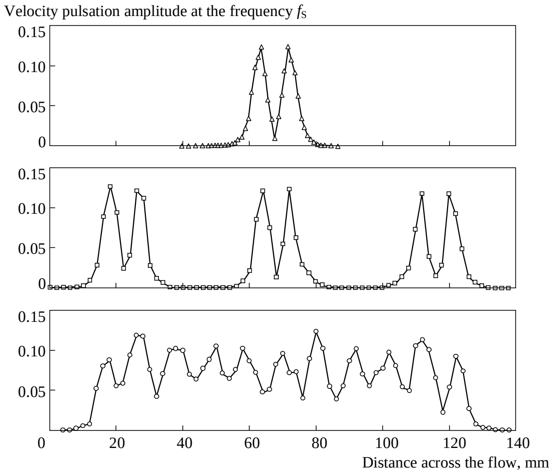

Fig.3 Distributions of the velocity pulsation amplitude, measured across the flow for 1, 3 and 10 cylinders for a laminar flow

As for the turbulent flow (Re = 490), the experiment showed that the interaction between the streets formed behind different cylinders also takes place in this case. The only difference from the laminar case is the fact that streets behind the cylinders are indistinguishable in a wake behind the array of 10 cylinders spaced by a given distance. A vortex wake has virtually no coherent component (the harmonic with the Strouhal frequency is almost indistinguishable in the pulsation spectrum against the noise level) and becomes similar to the turbulent jet.

Thus, our direct measurements confirmed the results predicted by the acoustic diagnostics data: the streets interact at closely arranged cylinders, which decreases the velocity pulsation amplitude in the vortex wake.

3. CONCLUSION

The method of acoustic diagnostics of hydrodynamic vortex flow was demonstrated for the vortical structure generated in an air flow behind an array of cylinders. This method allows one to measure vorticity and other parameters of flow. It was find the interaction between the separate vortices, which decreases the circulation in the neighboring Karman streets. The method of acoustic diagnostics can be used for investigation of flow structures in gas and liquids.

ACKNOWLEDGEMENT

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