DISTANT ACOUSTIC SENSING OF A VORTICAL WAKE FORMED BEHIND A GRATE OF CYLINDERS PLACED IN AN AIR FLOW

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Abstract

We report results of experimental research on scattering of a plane ultrasonic wave by a vortex wake formed in an air flow behind a lattice of vertical cylinders that is periodical in the direction normal to the incident flow. Investigations were carried out in a wind tunnel for two Reynolds numbers Re=75 and Re=500, for different number of cylinders in the lattice and different periods of the lattice $g=2.5\div1.5d$, where d is the diameter of the cylinders. The measured parameters of scattered waves were used for quantitative evaluation of a degree of transverse correlation of vortex wakes past the cylinders for different Reynolds numbers. Results of analysis of characteristics of the scattered sound are compared with data of direct measurements by hot-wire anemometers and with data obtained by other authors.

Introduction

Laboratory remote acoustic diagnostics of vortex and temperature pulsations in air flows has been used for a series of well-investigated currents: vortex Karman street behind a round cylinder [1-3], vortex ring [4], vortex behind a heated cylinder [5], floating thermic [6], and heated jet [7].

Recently, attention of researchers has been focused on a wake past a lattice of round cylinders placed in a plane-parallel air or water flow [8-13]. Visualization of such flows (see [8] and the literature cited therein) undertaken by different researchers revealed that vortex wakes formed behind different cylinders may interact, which in turn may lead to synchronization of oscillations in the flow and to formation of various types of currents [8-10], depending on parameters of the lattice and Reynolds number ($\mathrm{Re} = U_0 d/\nu$, where U_0 is the velocity of the incident flow, d is the diameter of the cylinder and ν is kinematic viscosity of air).

Researches on vortex structures past lattices of cylinders indicate that the distance g between cylinders in the direction normal to the incident flow is the control parameter of the flow, given invariable number Re of the incident flow. Depending on the value of this parameter, vortex wakes forming a lattice can be classified as weakly interacting ($g \geq 4.5d$) and strongly interacting ($g \leq 2.5d$) ones.

The weakly interacting wakes (see, e.g., [8, 10, 11]) are characterized by formation of an individual Karman street past each cylinder; whereas strong spatial inhomogeneity in the direction normal to the flow (along the lattice) is typical of the strongly interacting wakes. Visualization performed in [10] for a wake behind two cylinders with $g=2.5d$ demonstrated pronounced asymmetry of the vortex streets behind the different cylinders. Visualization of the flow past a lattice of 21 cylinders for the case of strong interaction and different Reynolds numbers [12] showed that the vortex wake is a set of “clusters” inside which the flow is a completely synchronized set of Karman streets. Location of these clusters and the amount of the streets within each cluster change at random.

All the above mentioned researches on vortex wake synchronization in air or water flows were mainly experimental and basic conclusions on the character of flows were made from snapshots. Remote acoustic diagnostics enabled us to estimate quantitatively the degree of synchronization of vortex wakes behind different cylinders for different flow parameters (Reynolds number Re, lattice period g, and number of cylinders in the lattice). Results of experiments on sound scattering were compared with data of direct measurements of vortex pulsations in the wake past a lattice of cylinders taken by hot-wire anemometers).

Results of experiments on sound scattering

Experiments were carried out in an air flow in a low-turbulent (the level of turbulent velocity pulsations in the incident flow was less than 0.4 %) wind tunnel with the size of the operating part being 30x30x120cm^3.

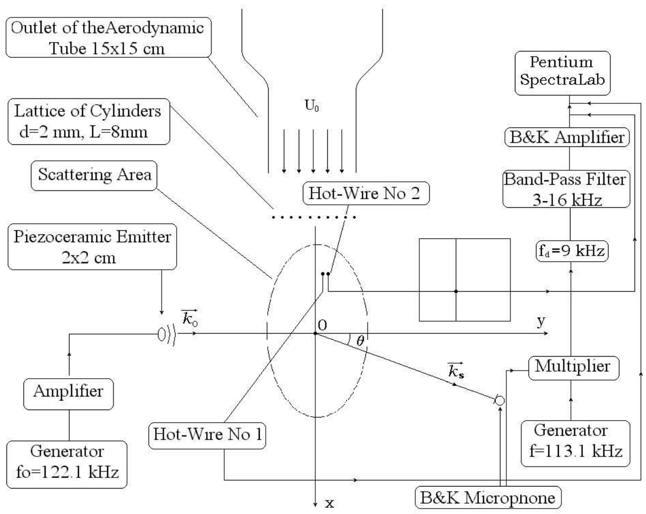

Figure 1. Schematic of the experiment.

We examined scattering of ultrasound with frequency f_0 =122.1 kHz by a vortex flow behind a lattice of vertically arranged cylinders having diameter d=2 mm and length 30 cm. The cylinders were arranged equidistantly in a series across the flow with the period g=(2÷24)d at a distance of 30 cm from the confuser outlet. The velocity of the incident flow was varied so as to investigate scattering for both laminar (Re = 75) and turbulent (Re = 500) flows. The number of cylinders varied from one up to ten. We took as a source of ultrasound a piezoceramic emitter with size a=2x2cm^2 . The emitter was placed at a distance of 65 cm from the center of the street, which corresponded to the Fraunhoffer zone. A high-frequency 4135 B&K microphone was used for measuring parameters of ultrasound. The microphone was placed on a movable bar at a distance of 1.6 m from the center of the scattering region and its position was varied in the angular range from 45 up to -45 degrees relative to the direction to the source of ultrasound. Measurements of spectral characteristics of scattered signal were performed with my means of computer.

It is known (see, for example, [1]) that spatial spectrum of the sound scattered at an infinite "ideal" vortex Karman street is a set of harmonics propagating symmetrically to the direction of the incident sound. The amplitude of each harmonic is proportional to vortex circulation in the street Γ. The frequency of each harmonic is shifted relative to the frequency of incident sound f_0 by $\Delta f_n = n \cdot f_{sh}$, $n = \pm 1, 2 ...$ that is multiple to vortex shedding frequency (the Strouhal frequency f_{sh}).

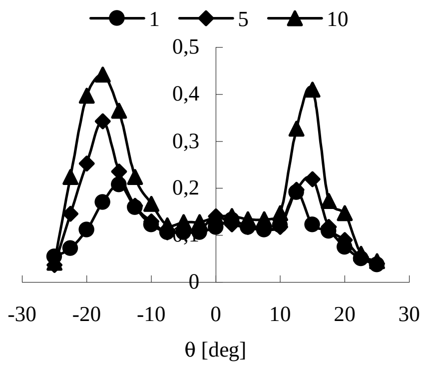

Figure 2. Amplitude of scattering at the +1-st and −1-st harmonics depending on the angle of scattering θ for Re = 75 for 1, 5, and 10 cylinders.

Since each individual vortex scatters sound mainly forwards, as a rule the +1st and –1-st harmonics are observed in experiment only. Directivity patterns of the +1st and –1-st harmonics were measured for a different number of cylinders and for two Reynolds numbers. Results for root-mean-square amplitude of harmonics at 3 Hz are presented in fig. 2 for 1, 5, and 10 cylinders (Re=75).

An increase in the number of cylinders in the lattice (i.e., an increase in the number of Karman streets) leads to increasing amplitude of the scattered signal. An average amplitude of the 1-st harmonic ($b(N) = \frac{A_{+1} + A_{-1}}{2}$, where A_{+1} and A_{-1} are the amplitudes of the +1-st and −1-st harmonics, respectively) is plotted in fig. 3 *versus* the number of cylinders N in the lattice for a constant lattice period g=4d and Reynolds number Re=75.

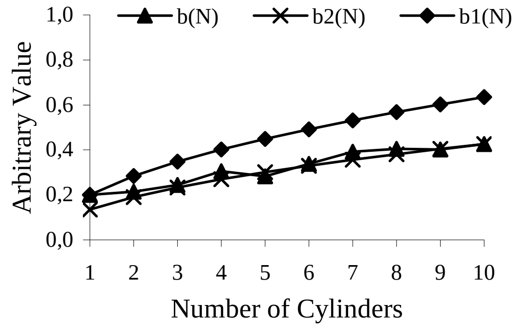

Figure 3. Amplitude of the 1-st harmonic versus number of cylinders for Re=75.

Two approximations of this dependence by a power function ($\sqrt{N}$, where N is the number of cylinders in the lattice) are also given in fig. 3. The curve $b1(N)$ is plotted by the formula $b1(N) = a_1\sqrt{N}$, where a_1 is the amplitude of scattered sound in a wake behind one cylinder obtained in experiment, and the curve $b2(N)$ corresponds to the formula $b2(N) = a_{10}\sqrt{N/10}$, where a_{10} is, respectively, the amplitude of scattered sound in a wake behind ten cylinders. Comparison of data of the experiments and the theoretical plots shows that in our experiment the amplitude of scattered signal increases slower than the root of the number of scatterers (the number of vortex wakes): the curve $b2(N)$ gives a much better approximation of data of the experiment than the curve $b1(N)$.

The situation is different for Re=500. Average spectral amplitude of scattering at the 1-st harmonic *versus* number of cylinders is plotted in fig. 4. Clearly, this dependence is ideally approximated by the function $\sim\sqrt{N}$.

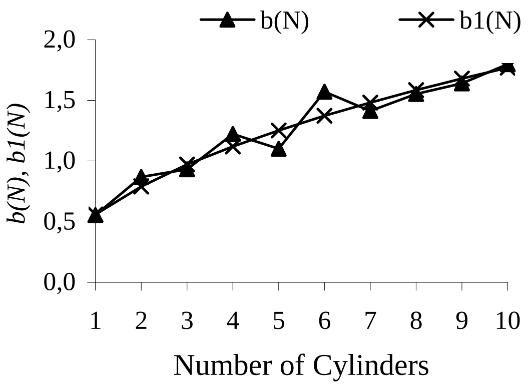

Figure 4. Amplitude of the 1-st harmonic *versus* number of cylinders for Re=500.

To elucidate the reason for different dependence of sound amplitude on the number of cylinders we made detailed measurements of velocity fields in vortex wakes past lattices of cylinders.

Measurements of vortex velocity field by hot-wire anemometers

Direct measurements of vortex velocity field were carried out by means of two hot-wire anemometers. Position of the sensors along and across the flow was varied with the aid of the co-ordinate frame. Lateral section of velocity pulsations was measured at a distance of 25*d* from the lattice of cylinders for Re=75 and 10*d* for Re=500. Signals from the sensors after amplification and filtration were transmitted to computer for processing by special software. Thus we measured

- amplitude of velocity pulsations *V* as a function of coordinate across the flow for different number of cylinders and fixed distance between the cylinders for two Reynolds numbers: Re=75 and Re=500 (fig. 5 *a*,*b* and fig. 6 *a*,*b*);
- values of coherence function and phase difference as a function of distance between them in the direction normal to the flow for Re=75 and Re=500

Velocity pulsation profiles for the wakes behind 3 and 10 cylinders are plotted in figs. 5 and 6 for Re=75 and Re=500, respectively. Figure 5*a* corresponds to the case when the cylinders are spaced apart by *g*=20*d* and the wakes do not interact. The velocity pulsation profile past each of the three cylinders repeats exactly the profile of the corresponding solitary Karman street.

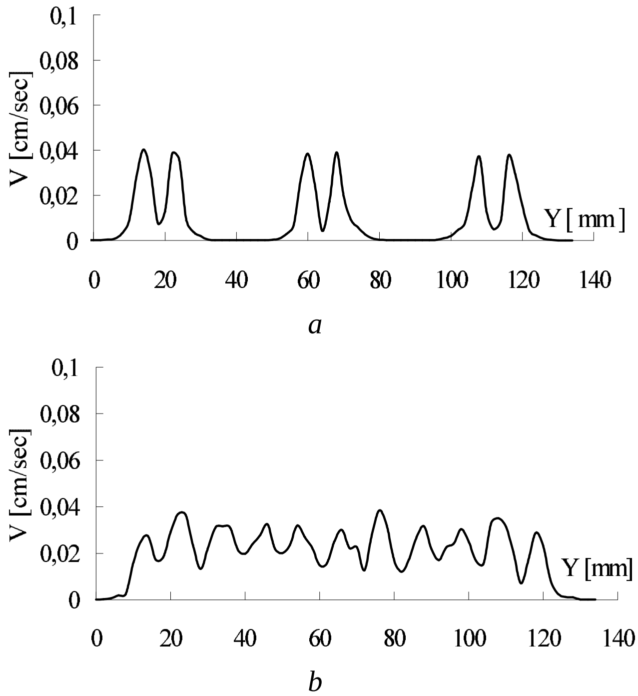

Figure 5. Lateral section of the amplitude of pulsations of the 1-st harmonic of vortex velocity field in the wake past 3 (*a*) and 10 (*b*) cylinders for Re=75.

At the same time, in the case of the wake past 10 cylinders (see fig. 5*b*) spaced apart by *g*=4*d*, the effect of street merging described in [8] is observed. Indeed, if there were no merging, the pulsation profile in the wake behind 10 cylinders would feature 20 maxima (2 behind each cylinder). Whereas in our case pair merging of streets occurs, i.e., one street is formed behind each pair of cylinders; correspondingly, the total amount of maxima is 11.

Analogous measurements (fig. 6*a*,*b*) for Re=500 demonstrate that an increase in Reynolds number results in disappearance of street merging (the same effect was observed in [9]). The width of each vortex street is much smaller in this case, and velocity maxima corresponding to different vortex rows in one Karman street are much closer for Re=500 than for Re=75. Velocity pulsation profiles past a lattice of 10 cylinders for Re=500 are random and it is impossible to isolate maxima corresponding to individual chains of vortices.

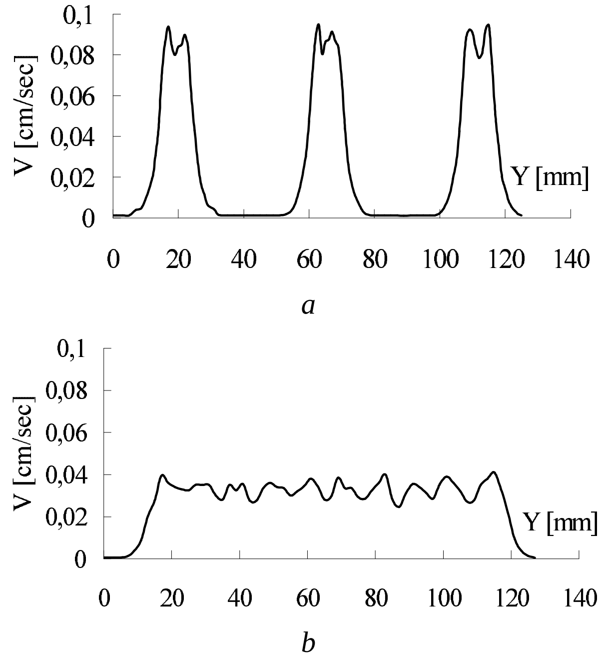

Figure 6. Lateral section of amplitude pulsations of the 1-st harmonic of vortex velocity field in the wake past 3 (*a*) and 10 (*b*) cylinders for Re=500.

The fact that the streets may merge in pairs or may exist independently does not yet give information about a degree of coherence of the vortex wake upon the whole. To determine the extent of synchronization of the vortex streets we measured coherence functions of signals obtained from two different hot-wire anemometers. The squared coherence function γ_{xy}^2 of two signals $x(t)$ and $y(t)$ is defined (see, e.g., [14]) as $\gamma_{xy}^2 = \frac{\left|S_{xy}(f)\right|^2}{S_x(f)S_y(f)}$, where $S_x(f)$ and $S_y(f)$ are power spectrum densities of the signals, and $S_{xy}(f)$ is the density function of the cross spectrum of the two signals:

$S_{xy}(f) = \hat{x}(f)\hat{y}^*(f) = \left|\hat{x}(f)\right|\left|\hat{y}(f)\right| \cdot e^{i(\hat{F}x(f) - \hat{F}y(f))}$, where $\hat{x}(f)$ and $\hat{y}(f)$ are Fourier transforms of the corresponding signal and the asterisk "*" stands for complex conjugation. The analog to coherence function in elementary statistics is squared correlation coefficient. We conducted experiments in a wake past 1, 3, and 10 cylinders for two Reynolds numbers: Re=75 and Re=500 for g=4d. Data of measurements verify that for Re=75 the characteristic scale of coherence in the direction transverse to the flow is about 10÷11d. From this it follows that for the total width of the wake of 50d we deal with approximately 5 uncorrelated scatterers ("enlarged" Karman streets). Consequently, we have *N/2* rather than *N* independent scatterers, which is the reason for the growth of scattering amplitude by the law $\sim\sqrt{N/2}$ (see fig. 3). For the case of Re=500, the characteristic scale of coherence is 5÷6d only, which corresponds to 20 uncorrelated scatterers along the 50d width of the wake. This results in the growth of the amplitude of scattered signal by the law $\sim\sqrt{N}$ (see fig. 5).

Conclusion

The results obtained in this research demonstrate that remote acoustic diagnostics can provide qualitative characteristics of a degree of synchronization of vortex streets formed past a lattice of cylinders. Consequently, this technique offers an alternative to vortex flow snapshots that are usually used as a proof of synchronization but do not provide quantitative estimates.

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