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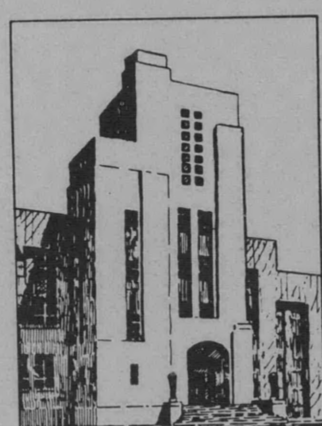
EXCITATION OF RESONANCE BY AIR FLOW

VOZBUZHDENIE REZONATOROV POTOKOM VOZDUKHA

[redacted]

by

D.I. Blokhintsev
Physical Institute, Academy of Sciences, U.S.S.R.



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ABSTRACT

This paper presents the results of an experimental investigation of the excitation of sound by an air stream blowing over the mouth of a resonator. It is shown that this excitation can be regarded as the result of resonance between the oscillations of a system of vortices, which are shed at the edges of the resonator, and the natural oscillations of the resonator.

INTRODUCTION

The origin of sound in the case of an air stream flowing about accoustic resonators constitutes a well-known phenomenon and has for a long time found application in musical wind instruments, whistles, and other similar equipment. In the current war this phenomenon has been utilized by the enemy in the so-called whistling bombs, designed to intensify the psychological effect. It has also found other, more expedient applications in military affairs. In some cases this phenomenon is harmful and must be combatted.

In sound measurements made under windy conditions, the wind can excite cavities which are occasionally present in the measuring equipment and as a result can be a source of considerable interference (for example in a sound receiver constructed of a system of piping for the purpose of improving the directional quality).

Strelkov[1] has recently investigated in detail the interesting phenomenon of the excitation of open wind tunnels, which can have catastrophic consequences.

Although the phenomenon of the excitation of resonance by an air stream has been known for a long time, complete understanding of the mechanism of such excitation nevertheless does not exist.

The fact that periodic pressure fluctuations, which are the origin of sound, arise even in those cases for which the body immersed in the air stream is not a resonator at all seemed to us to be of paramount importance.

These pulsations are excited by the formation of vortices in the region of flow instability at the boundary separating the stream and the "shadow", and they are known, in particular, as "vortical sound" or "Strouhal sound".

The frequencies f of these pulsations are determined exclusively by the shape of the body, by its position, by its dimensions, and by the flow velocity; thus

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[1]References are listed on page 10.

$$f = x\frac{v}{d} \qquad [1]$$

where x is a nondimensional coefficient (the Strouhal number) which is determined by the geometry of the flow, v is the flow velocity, and d is a characteristic dimension of the body.

It was natural to consider that these pressure pulsations were also the initial cause of excitation of the resonator. And, in fact, we succeeded in showing that excitation of the resonator occurs when the frequency of the vortices coincides with one of the natural frequencies of the resonator.

Vortices, however, do not constitute a rigid system and, therefore, it would be too primitive to think that we have here a case involving the ordinary phenomenon of resonance.

The oscillations of the resonator can themselves influence the oscillations of the vortices so that one can postulate the existence of a converse relation which is realized near resonance.

In the previously mentioned case of excitation of an open wind tunnel, investigated by Strelkov, it was also found that the oscillations are excited only for the condition that the frequencies of the vortices coincide with the frequencies of the tunnel. However, the question of whether these frequencies are peculiar to the vortices by themselves or whether they are determined entirely by the oscillations of the tunnel was left open.

In our work it is shown that the frequencies of the vortices exist by themselves, independent of the oscillations of the resonator, and that they are determined only by the velocity of the flow and by its geometry near the mouth of the tunnel. Furthermore, we obtain the correct order of magnitude of the effects assuming linearity of the oscillations. However, the measurements that we made are insufficient for making fully reliable conclusions about the nature of the converse influence of the resonator on the vortices or about the absence of such an influence. We have obtained some indication that this influence does exist in reality.

DESCRIPTION OF THE APPARATUS

A schematic diagram of the measuring apparatus is shown in Figure 1. The resonators that we investigated were boxes with strong metallic walls (two millimeter steel). One such resonator is shown in Figure 1. Its dimensions are also given there. Into the bottom of the resonator was screwed a measuring piezoelectric microphone M, which served as a pressure transducer. A General Radio sound meter (GR) was used as an amplifier whose varying voltage furnished the input to a Simens and Halske sound analyzer (SH). The latter has a filter with 27 bands of one-third of an octave each, beginning with a band at 40 cps. An electronic voltmeter (V) served as the measuring instrument. The microphone was calibrated with the sound meter.

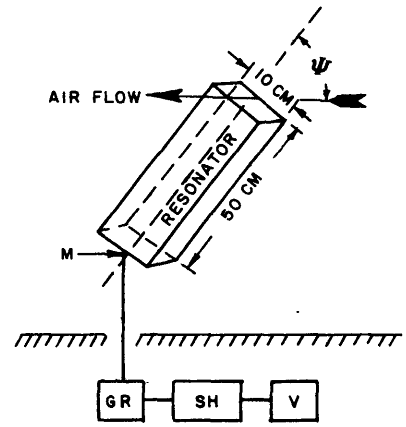

Figure 1

The measuring apparatus thus permitted not only a determination of the total pressure, but also a fairly detailed spectral analysis. The experiments were carried out in the CAHI* closed wind tunnel T-1, which was obligingly placed at our disposal by the director of the CAHI. The resonator was mounted on a centering device in the test section of the tunnel. This device made it easy to change the angle of attack ψ . The flow velocity was determined in the usual way with a CAHI manometer and a nozzle. The velocity range is from 4 to 30 m/sec. The comparatively high noise level of the tunnel constituted an unpleasant difficulty with regard to acoustic measurements. Therefore preliminary measurements of the energy distribution in the tunnel noise at various flow velocities were made.

For this purpose the microphone was mounted in a special wind-protected arrangement which eliminated vortex shedding on the body of the microphone. As will be seen from what follows, it was quite possible to separate the background noise of the tunnel from the effects of interest to us which arise near the mouth of the resonator.

A description of this wind protection, which was developed at PIAS* by the present author and I.I. Slavin, will be given in another place. The preliminary tests of this wind protection, which is especially suitable for high flow velocities, showed that it gives practically full protection from vortex shedding on the body of the microphone and to a considerable extent from effects caused by the turbulence of the wind.

TEST RESULTS

For clarity with regard to the character of the flow of the air stream about our resonators, an investigation of the flow picture around the resonator was made with a probe and silk threads. To investigate the flow within the resonator a wall of the resonator was replaced with one of

*Translator's Note: CAHI - Central Aero-Hydrodynamic Institute.
PIAS - Physical Institute of the Academy of Sciences.

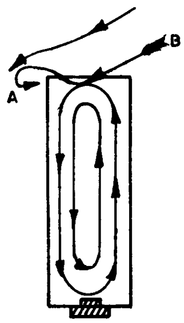

Figure 2

glass. In Figure 2 the flows which obtain at an angle of attack ψ=70 deg are shown. The line AB represents the unstable, dividing boundary which leads to vortex shedding. The angle of attack ψ = 70 deg was the most favorable for exciting the resonator. At angles of attack ψ = 30 deg the resonator was, in general, not excited in the velocity range from 0 to 40 m/sec. In addition, it was equally unexcited at ψ = 90 deg so that the excitation region extended approximately from 45 to 85 deg in the range $0 < V < 30$ m/sec. External circumstances did not permit us to investigate this interesting aspect of the phenomenon in greater detail.

The basic idea of the test consisted in eliminating by means of appropriate damping the possibility of natural oscillations arising in the resonator, so that the pressure pulsations measured by the microphone would have to be attributed completely to the vortex-shedding phenomenon occurring on the unstable dividing boundary AB. We expected frequencies independent of the natural frequency of the resonator and determined, in accordance with Equation [1], by the geometry of the flow and its velocity. Such frequencies were, in fact, detected. To carry out the indicated test the frequency characteristics of the resonator, which are depicted in Figure 3, were modified. In particular, resonant peaks are clearly seen in this figure, the first corresponding to the fundamental (f_0=155 cps) and the second to the first overtone (f_1=460 cps).

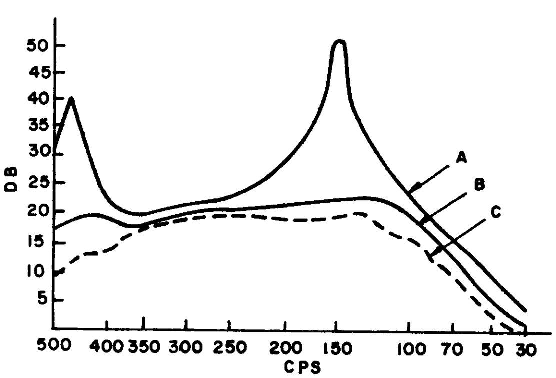

Figure 3

A damper, made of cotton wool and fine gauze, was then placed at the bottom of the resonator. Such a damper occupied slightly less than one-third of the height of the resonator and had an unavoidable influence on the flow within the resonator. However, in view of its slowness, this flow has no significance with regard to the phenomenon of interest to us. But the flow conditions at the mouth remained practically unchanged. Thus, this damper did not change the aerodynamic conditions, but radically altered the picture of the natural oscillations; the resonator became an aperiodic system, and the characteristics of the damped resonator, as seen in Figure 3, almost coincided with the characteristics of a measuring microphone located outside of the resonator. The damper completely eliminated the resonator.

Such a damped resonator was placed in the flow and the pressure pulsations arising at its mouth were spectrally analyzed for three velocities: 10, 20, 30 m/sec.

The results of this analysis are presented in Figure 4. Curve I represents the intensity of the pulsations in decibels within the damped resonator at an angle of attack $\psi=70$ deg and a flow velocity v=10 m/sec. In the figure the two maxima at f=65 cps and f=135 cps, which represent the fundamental and the first overtone of the vortical system, are clearly seen.

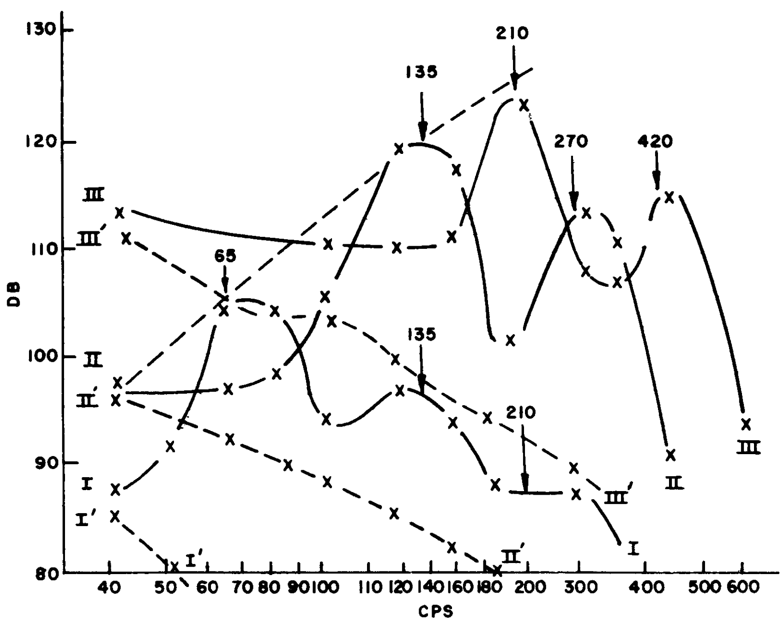

Figure 4

A third overtone is not revealed very clearly and results only in a delay in the downward fall of the curve around 200 cps; the dotted curve I' represents the spectrum of the tunnel noise. As is evident, this noise spectrum fully permits the measurements that are of interest to us to be carried out. Curve II represents the spectrum of the pulsations at v=20 m/sec; curve II' shows the tunnel noise spectrum for these same conditions. The frequencies were obviously shifted in the increasing direction. Curves III and III' have the very same signifiance, but refer to v=30 m/sec. As constructed from the basic curves of Figure 4, the dependency of the fundamental frequency and the first two overtones of the vortical system on the

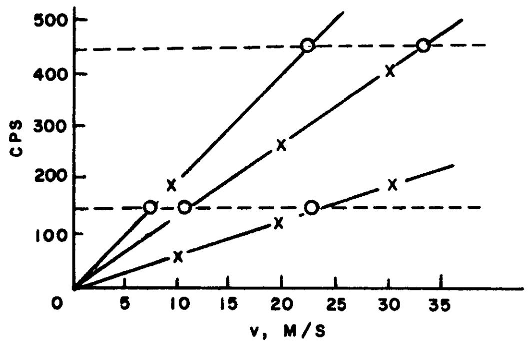

Figure 5

flow velocity are shown in Figure 5. This dependency completely satisfies the Strouhal formula [1], and if d denotes the length of the edge of the mouth of the resonator (our mouth is square with d=10 cm), the relation has the form:

$$f_n = x\frac{v}{d}n;\ \ x = 0.65;\ \ n = 1, 2, 3, \ldots \qquad [2]$$

As far as we know, only Holle, [2] who studied the vortical sound arising in flow about a cylinder, has observed overtones of the Strouhal frequency. The intensity of the pressure pulsations excited by vortex shedding, at least in regard to the fundamental tone, increases with the flow velocity in accordance with the law.

$$J = \alpha v^4 \qquad [3]$$

as can be obtained from the curves of Figure 4.

Thus, the pressure P of these pulsations is proportional to the aerodynamic pressure $q = \rho v^2/2$ (here ρ is the density of air), that is

$$P_n = \beta_n \frac{\rho v^2}{2} \qquad [4]$$

In Figure 5 the natural frequencies of the resonator (155 and 460 cps) are indicated by horizontal lines. Excitation of the resonator is to be expected at the points of intersection of these lines with the rays which represent the vortex frequencies. These points are indicated by circles. From the figure we see that excitation is to be expected at v=7.5m/sec (when the second overtone of the vortices coincides with the fundamental of the resonator), at v=13 m/sec (when the first overtone of the vortices coincides with the fundamental of the resonator), at v=22 m/sec (when the second overtone of the vortices coincides with the first overtone of the resonator, and the fundamental of the vortices with the fundamental of the resonator), and so on.

In the last of the enumerated cases biharmonic oscillation is to be expected. The existence of such an oscillation is more or less accidental ; in a different resonator it might or might not occur. Regions of excitation predicted on the basis of Figure 5 are, indeed, revealed in the test. The curves of Figure 6 show the intensity of the oscillations within the resonator as a function of the flow velocity. The intensities are determined with respect to a reference of 130 db. Curve I is obtained at $\psi = 70$ deg for d=10 cm. Three maxima A, B, C are distinctly seen on the curve. Spectral analysis of the oscillations shows that of these maxima A and B correspond to the fundamental of the resonator, and C to the biharmonic oscillation (the fundamental of the resonator and its first overtone).

The sound of the excited resonator is easily heard above the background noise of the tunnel. It is remarkable that a modification of the flow geometry, which changes the frequencies of the vortices, stops completely the sounding of the resonator. Such a modification can be attained if, for example, a screen is placed across the stream which flows about the mouth of the resonator. We tried installing a screen with cells 0.5 x 0.5 and a wire thickness of about 1 mm, and excitation of the resonator vanished.

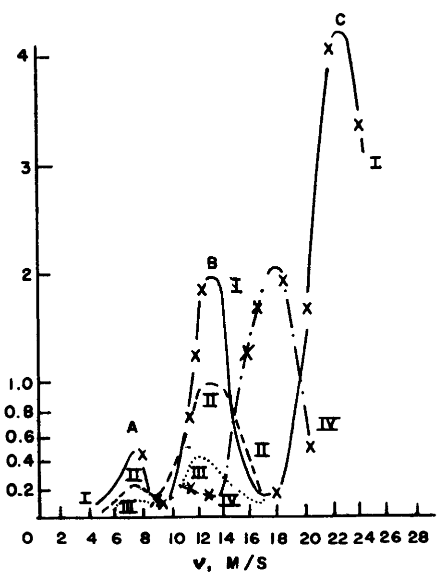

Figure 6

In Figure 6 the dependence of the excitation on the damping coefficient of the resonator is also demonstrated. Curve I refers to the undamped resonator, which has a damping coefficient h=12 sec^{-1}. This coefficient was determined by direct measurements in which the time of decay of the amplitude of the excited resonator was measured with a Neumann recorder. By installing dampers within the resonator (so as not to alter the flow conditions at the mouth of the resonator), resonators with damping coefficients h=25 sec^{-1} and h=55 sec^{-1} (curves II and III) were obtained. From these curves it is seen that the amplitude of the pressure at an excitation maximum turns out to be inversely proportional to the damping coefficient of the resonator.

Curve IV shows the effect of an increase of the length of the edge of the mouth of the resonator while preserving its natural frequency (the size of the resonator is 50 x 15 x 15 cm). According to formula [2], an increase in the excitation velocity by a factor of 1.5 is to be expected. As we see, the whole curve is, in fact, displaced in the direction of higher velocities. The velocity ratio is here 19:13 = 1.46, which within the limits of accuracy of the velocity measurements can be considered as coincident with 1.5. The damping coefficient of this resonator was equal to 22 sec^{-1}; therefore the maxima of curve IV are broader than the maxima of curve I.

The absolute value of the pressure, developed when the resonator is excited, is equal in order of magnitude to the aerodynamic pressure (actually, it is somewhat less). Thus, for example, for a velocity $v = 8$ m/sec the aerodynamic pressure $q = \rho v^2/2$ is equal to 5×10^2 bar, and the pressure in the resonator builds up to 1×10^2 bar (114 db); for $v=13$ m/sec we have q equal to 11×10^2 bar and the pressure equal to 4×10^2 bar (126 db).

DISCUSSION OF THE RESULTS

The results of our tests, which are presented above, very obviously show that the excitation of a resonator by a flow of air should be treated as a resonance phenomenon between the natural frequencies of the resonator and the fundamental or overtones of a system of vortices which are shed at the mouth of the resonator. This resonance occurs near the points indicated on Figure 5 by circles, i.e., at

$$\omega_s = 2\pi f_n = 2\pi x \frac{v}{d} n, \quad n = 1, 2, 3 \ldots, \quad s = 1, 2, 3, \ldots, \qquad [5]$$

where ω_s is one of the natural frequencies of the resonator and f_n are frequencies peculiar to the vortices themselves.

According to the results of our tests, it is possible to express the amplitude of the pressure of the s-th oscillation as

$$p_s = \frac{\rho v^2}{2} F_s \left(\frac{v}{d\omega_s}, \frac{h_s}{\omega_s}\right) \qquad [6]$$

where F_s is some nondimensional function and h_s is the damping coefficient of the oscillation. It is not possible to determine the form of this function in greater detail.

If the oscillations are considered to be linear, then for our case in which the resonator is a tube of constant cross section, closed at one end, it is easily calculated that the pressure p (on the bottom of the resonator where the microphone is located) is expressed by the following formula:

$$p = P\left[\left(\cos\frac{\omega l}{c} - Y_0 \sin\frac{\omega l}{c}\right)^2 + \left(\sin\frac{\omega l}{c}\,\frac{hl}{c}\right)^2\right]^{-\frac{1}{2}} \qquad [7]$$

where P is the external pressure applied at the mouth, which excites the oscillations of the resonator; ω is the frequency of the oscillations of this pressure; l is the length of the resonator; $Y_0 = 0.7\frac{\omega}{c}R$ is the end effect correction ($R = \sqrt{s/\pi}$ where s is the cross-sectional area of the resonator); and h is the damping coefficient. The value of h depends on the frequency, and therefore near resonance, i.e., for

$$\cos\frac{\omega l}{c} - Y_0 \sin\frac{\omega l}{c} = 0$$

it should have the value $h(\omega) = h(\omega_s)$. The resonance condition can be written in the form

$$\cos\frac{\omega_s L}{c} = 0, \quad \omega_s = \frac{\pi c}{2L}(2s+1), \quad s = 0, 1, 2, \ldots \qquad [8]$$

where $L = l + 0.7R$. At points of resonance we have

$$p_s = \frac{P_n c}{h_s l} \qquad [9]$$

In the case that we are considering P is the fluctuating pressure of the vortices which are shed at the mouth of the resonator. If the phenomenon should, in fact, proceed linearly, then the ratio of the pressures p_s at the maxima A and B of curve I, Figure 6, which refer to the same oscillation of the resonator (s=o), ought to have been equal to the ratio of the applied pressures P_n. These pressures are for A-P_3 at v= 8 m/sec, and for B - P_2 at v=13 m/sec. From Figure 5 we find the values of P_3 and P_2 at 10 m/sec (88 and 98 db, respectively) which we can then convert by relation [4] to the velocities of interest to us.

Then it is possible to find P_0 by formula [9] and to compare the resultant value with the test data (Curve I, Figure 6). The results are contained in the following table:

P	Theoretical	Experimental
85 db at $f_3 = \frac{\omega_1}{2\pi}$	120 db (A)	123 db (A)
103 db at $f_2 = \frac{\omega_1}{2\pi}$	138 db (B)	135 db (B)

Obviously, the results of the calculations with formula [9] are in good agreement with the measurement as far as order of magnitude is concerned (from the calculation the ratio is equal to 18 db, while in reality it is 12 db).

This discrepancy can be regarded as evidence of the nonlinearity of the phenomenon.

As we have already mentioned earlier, it is, of course, impossible to replace the system of vortices by a given external force; the oscillations of the resonator have in their own right an influence on the motion of the vortices and this fact is manifested by the failure of the proportionality assumption.

In conclusion, we are going to give a further calculation of the intensity of the sound radiated by the resonator. The flow of energy radiated by the resonator is equal to:[3]

$$\sigma = \frac{1}{2}\,\rho\, c\, X_0\, |\xi_0|^2\, s \qquad [10]$$

where ξ_0 is the velocity in the mouth, s is the area of the mouth, and $X_0 = \frac{\omega^2 s}{4\pi c^2}$ is the active part of the impedance of the mouth. On the other hand, at resonance, as is easily calculated, $\xi_0 = \frac{P_n c}{\rho c h_s l} = \frac{p_s}{\rho c}$ so that the sound pressure at a distance r from the resonator will be:

$$p = p_s \sqrt{\frac{s X_0}{4\pi r^2}} \qquad [11]$$

For our resonator $s=100$ cm^2, and $X_0=0.6 \times 10^{-2}$; at $r=200$ cm, p is equal to 1.1×10^{-3} p_s, i.e., p is 60 db less than p_s. If the curve of the tunnel noise is extrapolated to v=13 m/sec (see Figure 4, curves I' and II'), then we will obtain that the tunnel noise in this region of the spectrum amounts to approximately 75 db; on the other hand, p_s = 135 db, and, consequently, the intensity of the tunnel noise is equal to the intensity of the sound radiated by the resonator. We did not measure the intensity of this sound, but qualitative observation by ear does not contradict the above mentioned evaluation, since just at the indicated conditions the sound of the resonator can be heard fairly distinctly above the background noise of the tunnel. (It should be kept in mind that the tunnel noise is distributed more uniformly in the band width of the filter than the almost monochromatic sound of the resonator; thus, the above mentioned equality of intensities, strictly speaking, is concerned with sounds which have different spectral structures.)

In conclusion, I have the pleasant duty of expressing my thanks to my collaborators at the Acoustical Laboratory of the PIAS - Iu. M. Sukharevskii, Doctor of the Technical Sciences, I.I. Slavin, Batchelor of the Technical Science, and I.P. Zhukov, radio technician, for their advice and assistance in this work.

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2. Cavity resonators – Excitation
3. Vortices – Production
I. Title
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