Resonance Tubes in a Subsonic Flowfield

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Experiments have been carried out on the generation of strong pressure oscillations in resonance tubes placed in a subsonic flow. Triggering of the oscillations was achieved by prismatic objects placed upstream of the tube mouth. The oscillation amplitude depends on the flow velocity and geometrical parameters: shape of the tripping device, distance separating the tripping device from the tube mouth, and tube depth. In some cases, the oscillation amplitude is nearly equal to its theoretical maximum value. Below a critical velocity, the oscillations are small and irregular. At the critical velocity, the oscillation amplitude grows drastically. Its value depends on the geometrical parameters and was as low as 20 m/s in the reported experiments. A critical Strouhal number is introduced, and its value is almost independent of the tube length. It appears that the working mechanism of the resonator is the coupling of an instability wave developing in the shear layer behind the triggering device and the acoustic wave emanating from the resonator. The instability wave appears to propagate at 10% of the flow velocity.

Introduction

OVER 20 years ago, Sibulkin and Vrebalovich,[1] and later Vrebalovich,[2] conducted experiments on resonance tubes in a supersonic flowfield. They found that an oscillatory flow can be generated within a tube whose axis is parallel to the direction of the flow and that has a closed downstream end. The high-amplitude flow oscillations occur when a tripping device is located upstream of the open end of the tube. The devices used were either an airfoil ring[1] or a wedge.[2] In general, the experiments were conducted at supersonic speed ($M = 2.8$), but a few results were also reported for subsonic velocities ($M = 0.66$). These authors also observed a heating of the tube walls as in Hartmann-Sprenger tubes [3] (H.S. tubes). The latter device consists of a tube excited by a jet rather than by a parallel flow. At first, H.S. tubes were driven by supersonic, underexpanded jets.[4] Much later Sprenger[3] showed that oscillation could also be obtained with a subsonic driving jet (down to $M = 0.52$). Brocher et al.[5] found that it was even possible to generate oscillations at a jet Mach number as low as 0.12. Numerous papers have been devoted to H.S. tubes to investigate the oscillation mechanisms as well as the acoustic and thermal properties of the device. In contrast, no further work seems to have been done after the pioneer work of Sibulkin and Vrebalovich on tubes excited by a parallel flowfield. The purpose of this paper is to show that it is possible, in a subsonic flow, to achieve oscillation amplitudes with the device that are comparable to those obtained with optimized H.S. tubes.

It has been demonstrated[5] that a very thin needle mounted on the axis of the driving jet nozzle is sufficient to trigger strong pressure oscillation within these tubes. The authors now attribute the growing oscillation amplitude to the response of the boundary layer developing on the needle to sound waves reflected by the end plate of the tube and moving upstream.[6] Starting from rest, the oscillation grows until a limit cycle is reached[5] for which the maximum pressure oscillation amplitude is given by

$$\Delta p_{\max} \simeq 2\gamma\, M_j\, p_a + O(M_j^2)$$

where γ represents the ratio of specific heats, M_j the jet Mach number, and p_a the ambient pressure. Once the limit cycle is reached, the jet is fully swallowed by the tube during the compression phase.

In the case of a tube excited by a parallel flow, the jet Mach number M_j is replaced by the flow Mach number M. The maximum pressure amplitude in this case will be $2\gamma\, M\, p_a$.

From the fundamental point of view, it will be shown that the oscillation mechanism resembles that of an organ pipe.[7] The device constitutes a very simple, powerful sound source without moving parts. It is currently used by the authors to study the response of a boundary layer to intense sound waves[6] and could likely be used as a sound source for particle agglomeration, especially in difficult environmental situations where the use of moving parts is prohibited. It could also be used to generate an intense sound field for acoustic fatigue testing.

Experimental Setup and Results

The experiments were carried out in a subsonic wind tunnel with a 50×50 cm test section, 200 cm in length. The turbulence intensity was 0.2% at 25 m/s and 0.4% at 73 m/s. The resonators were located in the middle of the test section (Fig. 1). They had different lengths ($L = 200$, 355, and 730 mm), but all had the same square cross section (36×36 mm). The prismatic tripping devices of various shapes used in the test are shown in Fig. 2.

The tripping devices were mounted on rails to vary the distance d separating the device from the resonator entrance (Fig.

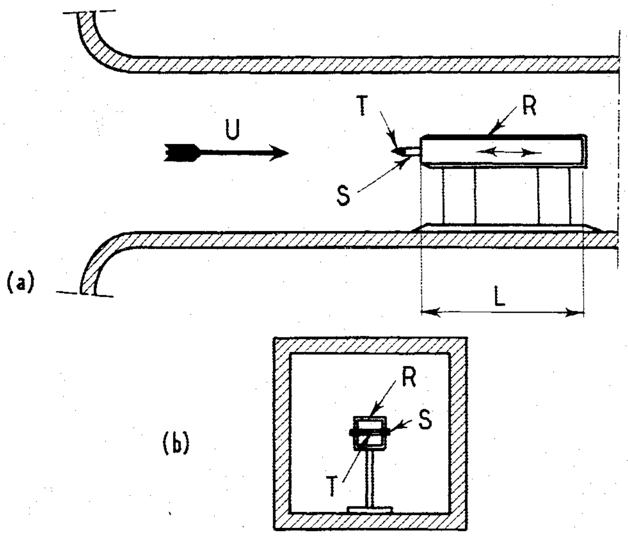

Fig. 1 Experimental setup (schematic): a) side view, b) front view; R = resonance tube; T = trip; S = trip support; L = tube length.

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2). The pressure fluctuations were measured at the end plate of the resonator with a Kistler gauge. Their amplitude was compared with the maximum amplitude ($\Delta p_{max} \cong 2\gamma\ M\ p_a$) achievable.

The experiments were carried out the following way: for a given resonator length and tripping device, the distance d was set at various values. For each d, the pressure amplitude was measured as a function of the wind tunnel velocity.

In general, the following observations could be made with increasing velocity:

$0 < U < U_{crit}$: The pressure oscillations were small and often irregular.

$U = U_{crit}$: For this critical velocity, which depends on geometrical parameters (L, tripping device shape, d), the oscillations became regular and of high amplitude. For certain configurations, there could be more than one critical velocity.

$U > U_{crit}$: The pressure amplitude increased with U but sometimes became unstable.

$U = U_{3H}$: A frequency jump to the third harmonic of the resonator was sometimes observed.

Pressure Oscillation Amplitude

The experimental results for the various geometrical configurations are given in Figs. 3-9. For a given tripping device and tube length, the distance d was varied over the range for which stable oscillations were observed. Then, with d fixed, the pressure oscillations were measured as a function of the flow velocity.

With Wedges

For $\alpha = 42.5$ deg and $L = 200$ mm, there is only one critical velocity which is superior or equal to 60 m/s, and the corresponding value of $\Delta p/\Delta p_{max}$ ranges between 50–60%. For $\alpha = 52.1$ deg, there are two critical velocities for certain values of d. With $d = 15$ mm, for instance, the lowest critical velocity is 35 m/s and gives a value of 13% for $\Delta p/p_{max}$. With increasing velocity, the amplitude diminishes until a second critical value of the velocity is reached (59 m/s) for which Δp represents 77% of Δp_{max}. With $\alpha = 73.7$ deg, one can also observe two critical velocities. At $d = 16$ mm, the first one is 33 m/s with $\Delta p/\Delta p_{max} = 10\%$ and the second one is 50 m/s with $\Delta p/\Delta p_{max} = 86\%$. It can be observed that the critical velocities giving high pressure amplitudes are a decreasing function of the wedge angle, whereas the optimal value of $\Delta p/\Delta p_{max}$ is an increasing function of the wedge angle: 59% for $\alpha = 42.5$ deg, 77% for $\alpha = 53.1$ deg and 87% for $\alpha = 73.7$ deg. Hence, for $L = 200$ mm, it is possible to design a resonator giving pressure oscillations with an amplitude close to the maximal theoretical value.

In Fig. 4, the pressure amplitude is plotted as function of the flow velocity for the two largest wedge angles. The various domains described are clearly seen.

In general, for $L = 355$ mm, there is only one critical velocity for which large pressure amplitudes are observed. It does not depend on the wedge angle. The optimal value of $\Delta p/\Delta p_{max}$ is 87% for $\alpha = 42.5$ deg, 90% for $\alpha = 53.1$ deg and 100% for $\alpha = 73.7$ deg.

At high velocities ($U \geq 61$ m/s), for $\alpha = 53.1$ deg when $10\text{mm} \leq d \leq 12\text{mm}$, the frequency jumps to the third harmonic of the resonator. Although the pressure oscillations are very regular, their amplitude is much smaller than Δp_{max}.

In Fig. 6, the amplitude is shown as a function of the flow velocity. It is seen that above the critical velocity, the pressure amplitudes lie between 85 and 90% of Δp_{max} over the velocity range tested, almost independently of the wedge angle.

For $L = 730$ mm, the critical velocity is quite low and is a decreasing function of the wedge angle, being about 25 m/s for $\alpha = 42.5$ deg and 20 m/s for $\alpha = 73.7$ deg. However, the optimal amplitudes are substantially smaller for this long resonator than for the shorter ones. The maximum value of $\Delta p/\Delta p_{max}$ is only 61% (for $\alpha = 53.1$ deg and $d = 20$ mm) on the first harmonic of the resonator. At higher velocities, for the two largest wedge angles, the frequency jumps to the third harmonic, and for $\alpha = 53.1$ deg, the amplitude can be quite high, reaching 75% of $\Delta p/\Delta p_{max}$ at $d = 26$ mm.

The tendency to jump to the third harmonic for longer resonators may be explained in the following way. The compression front (see Ref. 7, p. 96) steepens as it moves down the tube, the steepening being an increasing function of the resonator length. This wave deformation produces harmonics that become important for long resonators. While running ex-

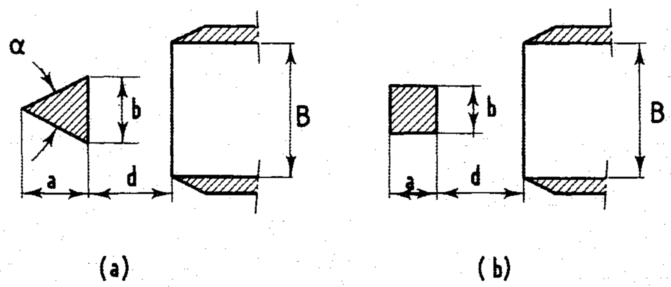

Fig. 2 Shapes and location of tripping devices: a) wedge trips—1) $a = 9$ mm, $b = 7$ mm, $\alpha = 42.5$ deg; 2) $a = 9$ mm, $b = 9$ mm, $\alpha = 53.1$ deg; 3) $a = 6$ mm, $b = 9$ mm, $\alpha = 73.7$ deg; b) square trip—$a = b = 9$ mm.

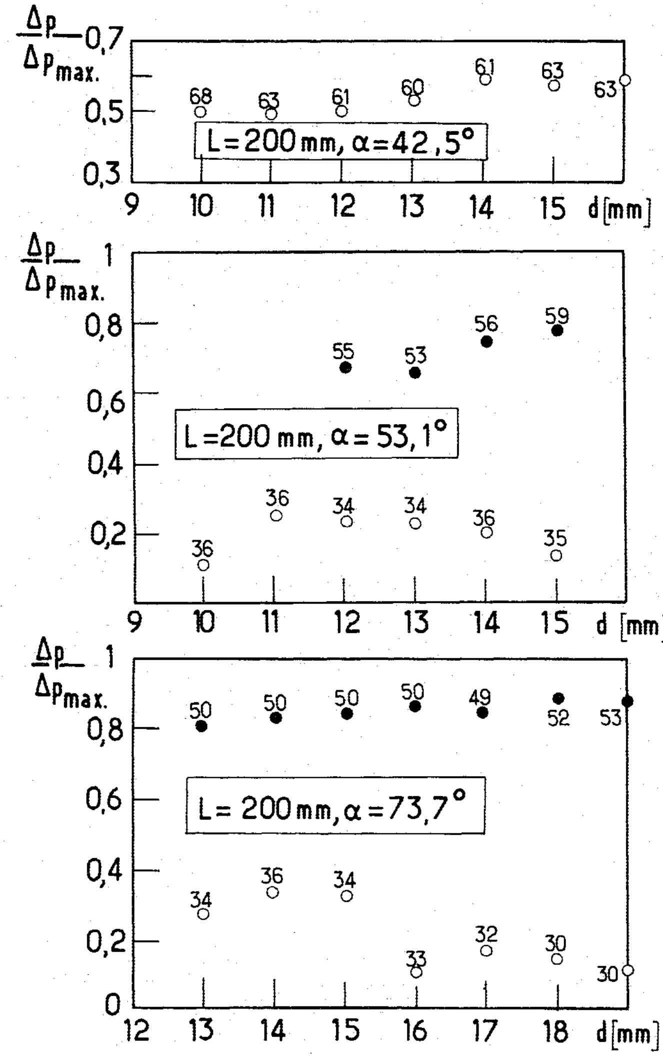

Fig. 3 Pressure amplitude at the end plate of the resonance tube ($L = 200$ mm); O, at lowest critical velocity; •, at second critical velocity (corresponding value of velocity given in m/s on each experimental point).

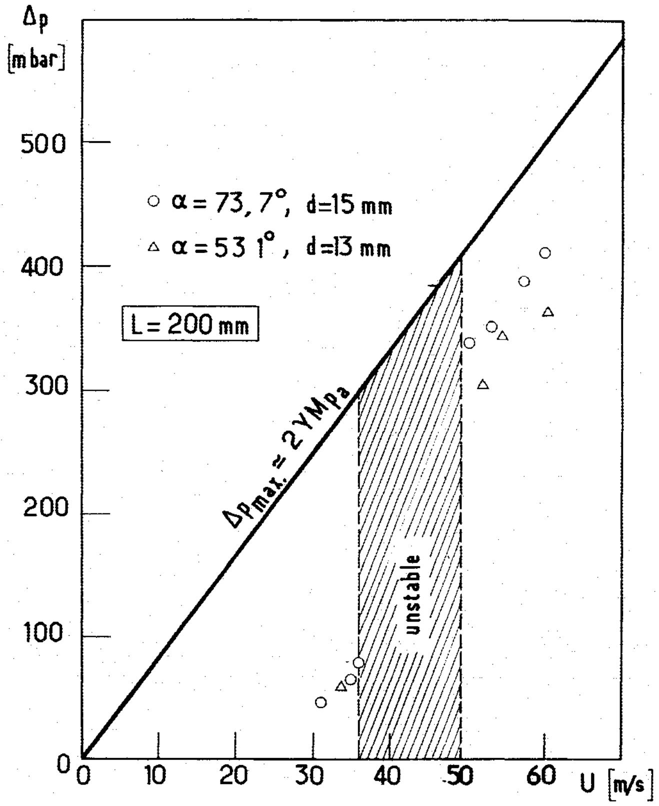

Fig. 4 Pressure amplitude as a function of flow velocity ($L = 200$ mm).

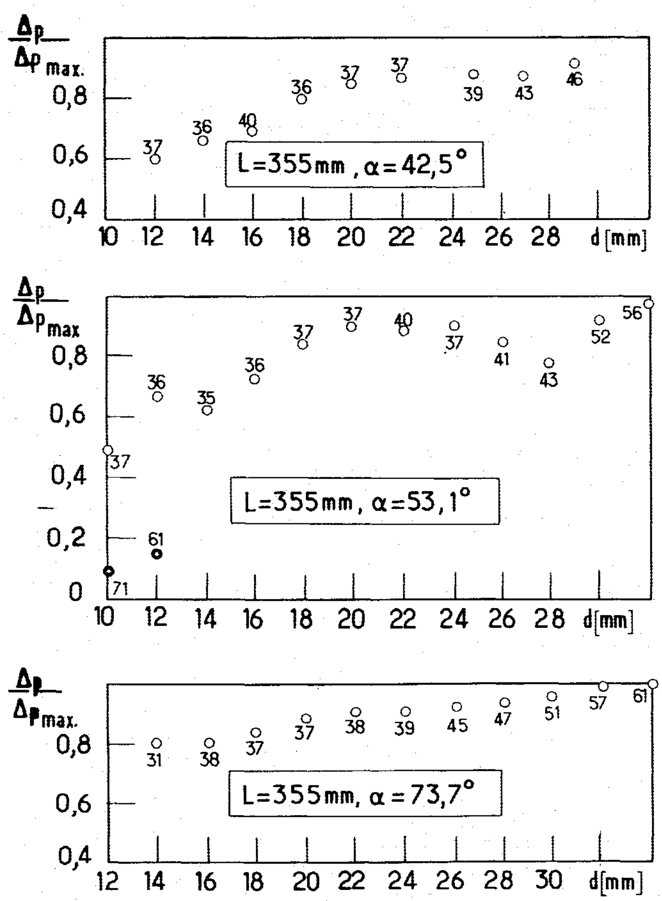

Fig. 5 Pressure amplitude at the end plate of the resonance tube ($L = 355$ mm): O, at the lowest critical velocity; o, at second critical velocity (third harmonics) (corresponding value of velocity given in m/s on each experimental point).

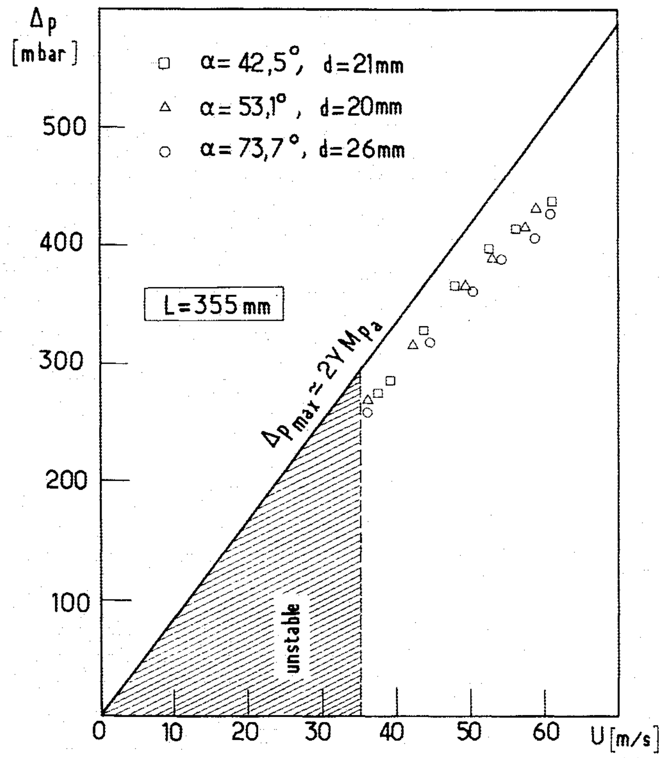

Fig. 6 Pressure as a function of flow velocity ($L = 355$ mm).

periments on the longest resonator, the pressure signal was sent on a FFT Frequency Analyzer, and it was observed that the third harmonic grows with increasing flow velocity and suddenly dominates the first harmonic. This growth also corresponds to a result of the steepening theory, which shows that the steepening is an increasing function of the velocity gradient $\partial u/\partial x$. This gradient is of the order U/L, where L represents the tube length. Hence, for a given L, the steepening will grow faster as the flow velocity increases. As a consequence of the wave steepening, an initially pure harmonic signal will be distorted and contain more and more higher harmonics as it gets distorted. If a coupling of these higher harmonics with flow phenomena in the wake of the tripping device occurs, resonance on these higher frequencies may then appear.

In Fig. 8, the pressure amplitude is given as a function of the flow velocity. For $\alpha = 42.5$ deg, above the critical velocity ($U = 26.1$ m/s), the amplitude grows steadily with U. For $\alpha = 73.7$ deg, the amplitude grows on the first harmonic, then jumps on the third with a sudden drop. For 30 m/s $< U <$ 43 m/s, the oscillations are unstable. Above $U = 43$ m/s, the oscillations are again stable on the third harmonic and grow with U.

With Squared Cross-Sectional Trip

Since it was observed that on the two shortest resonators the pressure oscillation amplitude is an increasing function of the wedge angle, it was thought that the vortices in the wedge wake could be responsible for triggering the oscillation. The wider the angle, the stronger the vortices' strength should be, and so the triggering. It was therefore decided to run some experiments with a rod with a squared cross section. The results of these measurements are shown in Fig. 9.

For $L = 200$ mm, a first critical velocity was observed. For $d = 10$ mm, this velocity is only 28 m/s, with $\Delta p/\Delta p_{max} = 52\%$. The existence of a first critical velocity was already observed with two wedges ($\alpha = 53.1$ and 73.7 deg). But here, the critical velocity is even smaller and the value of $\Delta p/\Delta p_{max}$ substantially larger. For $d = 18$ mm, the second critical velocity is 56 m/s and gives a $\Delta p/\Delta p_{max}$ of 87%. This percentage is comparable to what was obtained with the largest wedge angle.

For $L = 355$ mm, two critical velocities are also observed for 12 mm $< d <$ 16 mm. With $d = 16$ mm, the first one is 23 m/s and gives a $\Delta p/\Delta p_{max}$ of 33%. The second one is 35 m/s, with a $\Delta p/\Delta p_{max}$ of 79%. This result is somewhat less satisfactory than with wedges. For $L = 730$ mm, the oscillations were generally on the third harmonic and of relatively low amplitude.

To summarize the results obtained with the squared cross-section rod, it can be said that the performance of the resonators is in general not as good as with the wedges, except for the shortest resonator at low velocity. It is likely that the squared shape excessively disturbs the flow at the entrance of the resonator.

Oscillation Frequency

The fundamental frequency of a resonator closed at one end is given by

$$f = [c/4(L + \Delta L)]$$

where c represents the speed of sound and ΔL the end correction. Measuring the frequency enables one to calculate the end correction ΔL. The results are given in Table 1. The values of ΔL have been computed taking a speed of sound of 348 m/s, corresponding to a laboratory temperature of 20° C. Hence,

Table 1 End correction ΔL

L [mm]	200	355	730
f [Hz]	400	229	113
ΔL [mm]	17.5	24.9	39.9

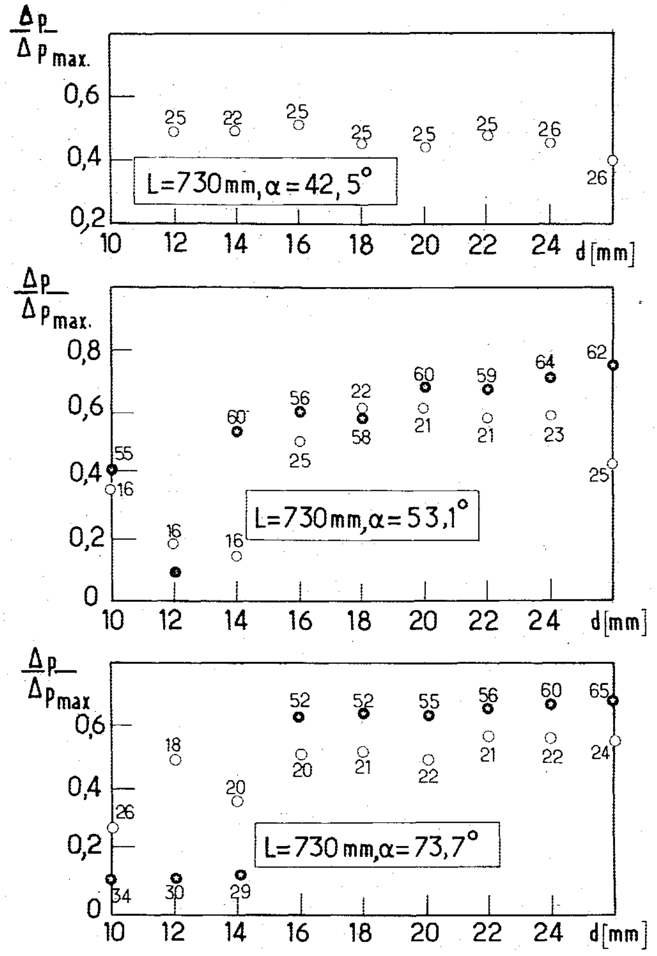

Fig. 7 Pressure amplitude at the end plate of the resonance tube ($L = 730$ mm): O, at lowest critical velocity; ʘ, at second critical velocity (third harmonics) (corresponding value of velocity given in m/s on each experimental point).

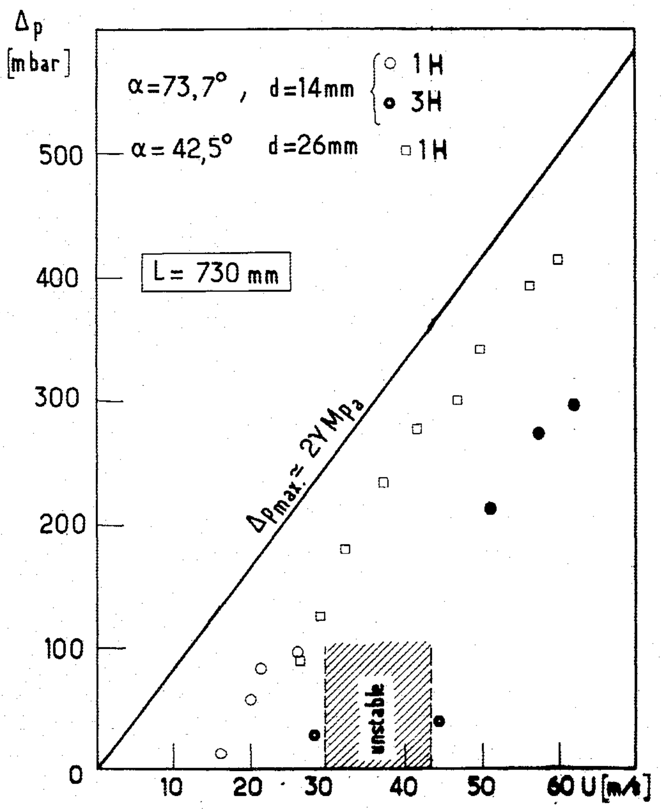

Fig. 8 Pressure amplitude as a function of flow velocity ($L = 730$ mm).

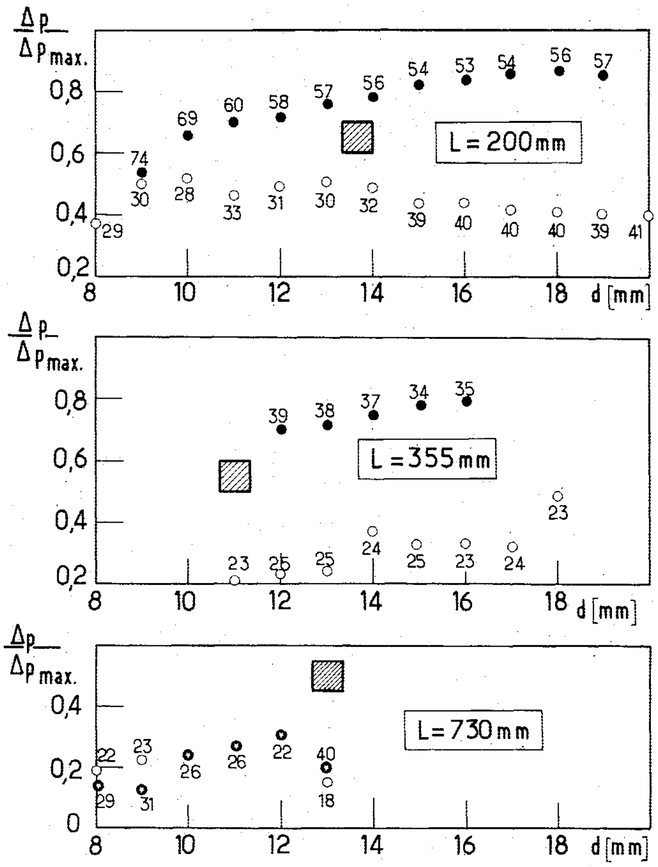

Fig. 9 Pressure amplitude at the end plate of the resonance tube, squared cross-sectional trip: O, at lowest critical velocity; •, at second critical velocity (first harmonic); ʘ, at second critical velocity (third harmonic) (corresponding value of velocity given in m/s on each experimental point).

Table 2 Critical Strouhal number and velocity ratio K

L [mm]	200	355	730	
α [°]	73,7	53,1	53,1	
d [mm]	15	20	20	
f [Hz]	400	229	113	339
U [m/s]	50	36	21	60
$S_{crit} = K$	0,120	0,127	0,107	0,113

the end correction is an increasing function of L. This is in contrast to the classical end correction, which depends on the tube diameter only. It has also been observed that the oscillation frequency is not sensitive to the distance d.

As has been described, for each resonator there exists a critical flow velocity at which the pressure oscillations suddenly increase in amplitude and are generally close to Δp_{max}. A critical Strouhal number may be defined as

$$S_{crit} \equiv (fd/U_{crit})$$

where d has been chosen as the characteristic length. Alternatively, the side of the squared cross section (B in Fig. 2) of the resonator could have been chosen. However, for reasons that will become apparent, it appears physically more appropriate to take d as the characteristic length. Values of S_{crit} are given in Table 2. It is seen that it varies very little with the resonator length, which means that U_{crit} is approximately proportional to the resonator fundamental frequency.

Comparison with Organ-Pipe Physics

In a recent paper,[8] Fletcher and Thwaites describe the state-of-the-art in the understanding of the physics of organ pipes. Indeed, up to recent years, the physical processes underlying organ-pipe sounding were not very well-known, and much empiricism was used to design a "good" organ pipe. Reading Fletcher and Thwaites made the authors of this paper think that certain basic processes of organ pipes' functioning are also fundamental to the resonator, even if many of the peculiarities observed in this device cannot be explained for the time being.

In an organ pipe, a sheet of air with a velocity ranging from 20–30 m/s flows out of a narrow slit and impinges on the upper lip of the pipe mouth. It has been observed that the jet, under the influence of pressure waves, makes a snake-like motion that propagates with a speed slightly inferior to half the jet velocity at a given point. As the mean jet velocity dissipates, the propagation velocity decreases with the distance to the slit. The amplitude of the lateral motion grows exponentially[9,10] in certain cases. In order for the jet to excite stationary waves in the pipe, the wiggling motion of the jet around the upper lip has to be at a particular phase angle with the wave motion within the pipe. The time required for a fluid element to cover the distance separating the jet slit to the upper lip is, therefore, a dominant factor and depends on the jet velocity, of course. Below a certain velocity, no sound is emitted by the pipe. At a certain critical velocity, the pipe is suddenly resonating at the fundamental frequency. Then, over a certain velocity range, the emitted sound remains on the fundamental frequency. If the velocity is further increased, a frequency jump to a higher harmonic occurs. It is therefore observed that several phenomena described by Fletcher and Thwaites for the organ pipe correspond to those occuring with resonators in a flowfield. One may imagine that the shear layer developing in the trip wake and impinging on the resonator mouth also makes a sinuous motion.

If one admits that the wave propagates within the shear layer with a speed equal to KU, where K is a constant that may be experimentally determined and U the wind tunnel velocity, the time Δt for the wave to travel from the back of the trip to the resonator mouth is equal to

$$\Delta t = (d/KU)$$

In order for coupling of the lateral motion of the shear layer and the acoustic waves within the resonator to occur, Δt must have a value close to the acoustical period of the resonator: $T = 1/f = 4(L + \Delta L)/c$. Hence, one may determine the value of K by the relation $K = fd/U$ and by considering the experimental conditions for which the observed oscillation amplitude suddenly increases. To this point, it may be observed that the velocity ratio K is identical to the critical Strouhal previously introduced.

Since S_{crit} varies little with L, neither does K, of course. This seems to confirm the idea that there exists a coupling between an instability wave in the shear layer generated by the tripping device and the acoustic wave within the resonator. Comparing this coupling to the one existing in organ pipes, it is noted that the velocity ratio K is much smaller for the shear layer (~ 0.1) than it is for the organ pipe jet (~ 0.5).

Another confirmation of the coupling is found for $L = 730$ mm. With $\alpha = 53.1$ deg (see Table 2), U_{3H} is roughly equal to three times the critical velocity for the first harmonic, so that the value of S_{crit} is almost the same at the two frequencies. With $\alpha = 73.7$ deg, the ratio of the two critical velocities is also not far from three.

Conclusion

It has been experimentally demonstrated that it is possible to produce intense flow oscillations within a tube placed in a subsonic flowfield. These flow oscillations are achieved by mounting a tripping device upstream of the tube entrance. The largest experimental oscillations observed are close to the theoretical maximum value. They were obtained with the wedge having the widest apex angle (73.7 deg) among the trip shapes tested. The origin of the oscillations appears to lie in the coupling of the trip wake with the acoustic waves propagating within the tube. Analogy with the physics of organ pipes has been shown. The device constitutes a very simple, powerful, sound source and can be used either for research of fundamental nature in aero-acoustics or for practical applications, such as aerosol agglomeration and acoustic fatigue testing.

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