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# SELF-EXCITED FLOW OSCILLATION IN AN ABRUPTLY EXPANDING CIRCULAR DUCT AS THE NOISE SOURCE

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The behaviour of oscillations in subsonic flow in a duct with a sudden enlargement of cross-section has been investigated experimentally. The mechanism of one type of oscillation has been found and explained. In this type of oscillation the resonant oscillation of a gas column in the part of a duct with constant cross-section is sustained by flow in the extended part of the duct. The flow is accompanied by periodically occurring and downstream moving annular vortices which close the feedback loop. The shadow graph visualization has confirmed the existence of this coherent vortex structure in the flow.

## 1. Introduction

In internal flows a rapid expansion of the cross-section of the duct causes flow separation and the occurence of stagnation regions. Such a configuration is not stable and very often induces self-excited flow oscillations which generate loud noise. The mechanism of such oscillations is frequently defined as the acoustic-flow feedback.

The group of flows in which oscillations can occur includes flows past cavities [1-3], orifices [4], expansion chambers [5] and ducts with rapid change in cross-section [6-9]. The object of the investigation presented here is self-excited oscillation occurring in subsonic flow in an outlet with a sudden cross-section increase at the end. Some experimental studies [6, 7] have been devoted to this phenomenon. The authors have considered this problem only from the point of view of technical application. Oscillation of such a type increases the jet mixing rate, so that the operation of various kinds of ejectors can be improved. No investigators have paid much attention to the mechnism of this oscillation. It has only been suggested that the jet periodically separates and reattaches to the wall of the expanded part of the duct. Previous investigators [8, 9] of oscillation in supersonic flow in similar configurations have shown that depending on the pressure difference at both ends of the duct several types of oscillation can occur. One can expect that many types of oscillation can also exist in subsonic flow.

Thus, the investigations reported on in this paper focused on the study of the mechanism of oscillation in subsonic flow in a duct with a relatively short collar and relatively low gas velocity.

## 2. Investigation facility

Fig. 1a shows a schematic diagram of the investigation facility. Air with controlled supply pressure ($p_0$) flows to a chamber lined with some absorbing material, in order to reduce partially the initial flow turbulence. From the

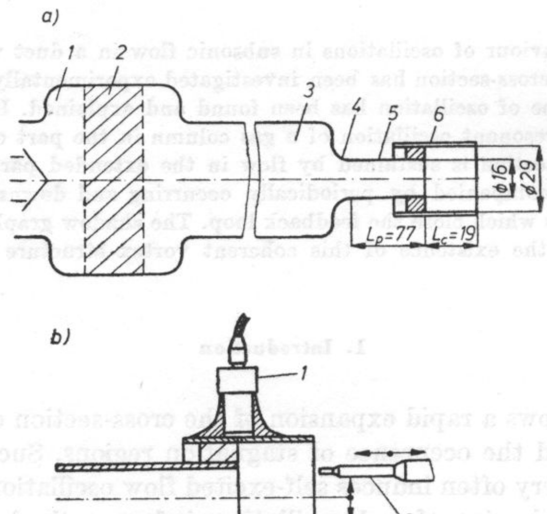


Fig. 1. A schematic diagram of the experimental facility

a) *1* – chamber, *2* – damping element, *3* – supply duct, *4* – nozzle, *5* – duct, *6* – collar; b) *1* – pressure transducer, *2* – thermoanemometer probe, *3* – microphone

chamber the air flows out through a duct with a relatively large cross-section to a convergent nozzle at the end. The nozzle is fastened by a duct with a movable collar, forming a channel with a sudden increase of cross-section.

The arrangement of the measuring equipment is shown in Fig. 1b.

Acoustic measurements were carried out with $B$ and $K$ equipment, using for spectral analysis a 2010 narrow-band analyser and a 2307 recorder. A 4133 1/8″ microphone with a 2619 preamplifier was placed in the near field (see Fig. 1b). The pressure pulsation inside the collar was measured using a Kistler (7031) piezoelectric transducer with a 5007 charge amplifier. Flow velocity measurements were carried out with a 55 *MOI* bridge and a 55 *D*10 linearizer. The cross correlation between the pressure and the flow velocity signal was performed by a 55 *D*70 *DISA* correlator with normalisation of input signals. The correlation functions were recorded on a 411 Watanabe recorder.

### 3. Results of measurements

The noise from such a type of flow oscillation was very distinct. Fig. 2 shows the spectra of sound emitted by the air flow in three different configurations (free jet, short collar and long collar). All measurements were carried

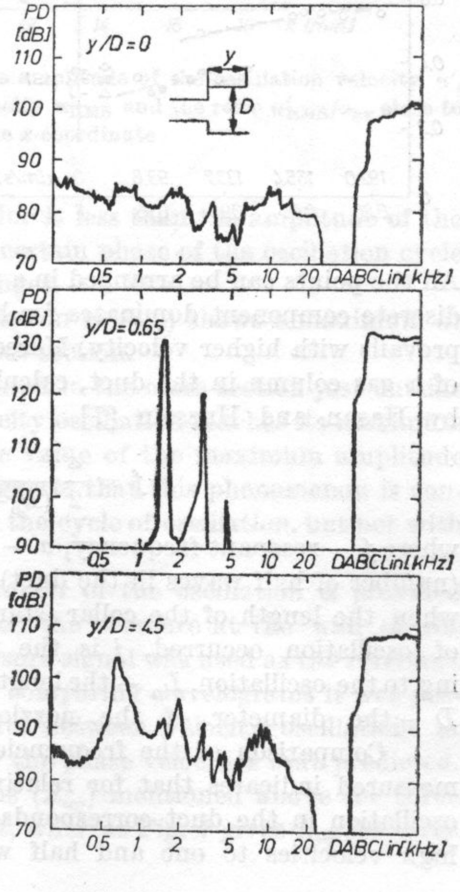


Fig. 2. Sound spectra

out for the same ratio of the ambient to the stagnation pressure (0.95), corresponding to flow velocity of 93 m/s. Strong flow pulsation occurred only for the duct with a short collar. The overall sound level was in this case about 30 dB higher than that for the other configurations. The noise spectrum showed a distinct discrete component and its harmonics.

Fig. 3 shows the dimensionless frequency of the sound spectrum versus the pressure ratio of flow velocity. The dark points mark the dominant components.

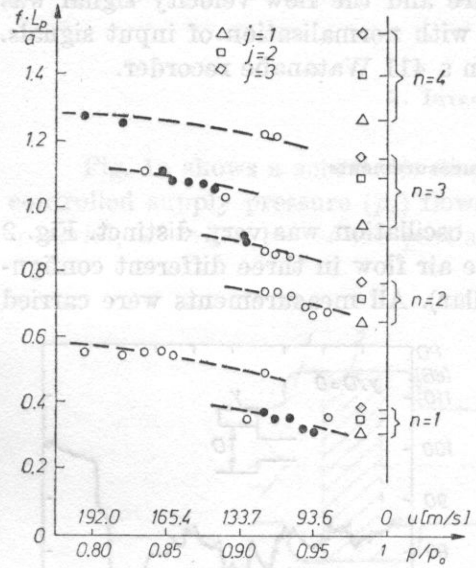


Fig. 3. Dominant frequencies in the sound spectrum

All the points can be arranged in a number of bands. The first harmonic of the discrete component dominates for lower flow velocity, whereas the second one prevails with higher velocity. Moreover, Fig. 3 shows the resonant frequencies of a gas column in the duct, calculated from the experimental formula given by Hasan and Hussain [7]

$$f = \frac{a}{2}\,\frac{n}{(L_p + 1.65L_c/j + 0.7D)},$$

where $f$ — resonant frequency, $a$ — the speed of sound, $n$ — mode of operation (number of half waves in the duct), $j$ — stage of operation defined as follows: when the length of the collar (starting from zero) was increased some range of oscillation occurred, $j$ is the number of successive ranges corresponding to the oscillation, $L_p$ — the length of the nozzle, $L_c$ — the length of the collar, $D$ — the diameter of the nozzle.

Comparison of the frequencies calculated from this formula and those measured indicates that for relatively low velocities the mode of resonance oscillation in the duct corresponds to half the wavelength and for relatively high velocities to one and half wavelengths.

The properties of the sound spectrum considered here are strictly connected with flow oscillation in ducts.

Fig. 4. gives the results of flow velocity measurements along the wall of the collar. The mean flow velocity at the wall is negative (the flow is from

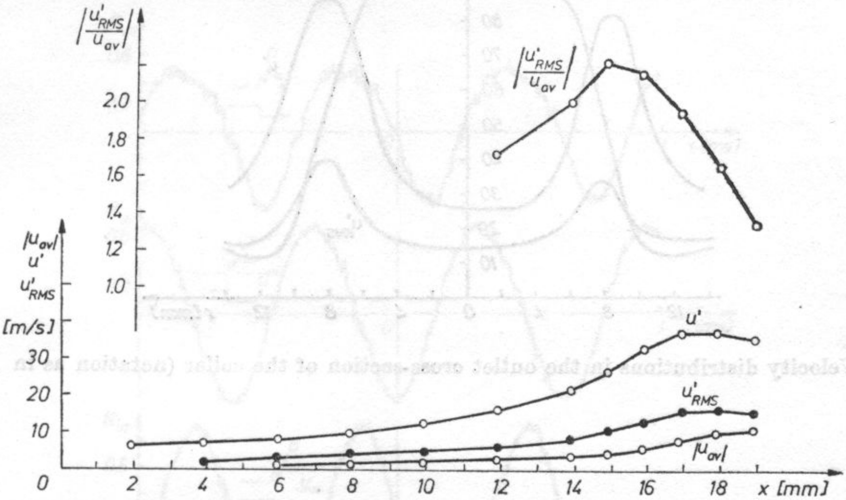


Fig. 4. Distributions of the mean velocity $u_{av}$, the amplitude of the oscillation velocity $u'$, the rms value of the amplitude of oscillation velocity $u'_{RMS}$ and the ratio $u'_{RMS}/u_{av}$ close to the collar versus the $x$-coordinate

the surroundings into the collar) and its value is less than tha amplitude of the velocity oscillation. This singnifies that in a certain phase of the oscillation cycle the direction of the flow in this region changes.

The relative amplitude velocity oscillation ($u'/u_{av}$) shows a maximum at a position 4 mm from the collar outlet cross-section.

Fig. 5 presents velocity profiles measured in the cross-section just outside the collar outlet. The amplitude of the velocity oscillation reaches its maximum value at the boundary of the jet. The large value of the maximum amplitude is very close to the mean velocity. This suggests that this phenomenon is connected with variation of the jet diameter in the cycle of oscillation, but not with turbulence.

Essential information about the character of the oscillation is provided by the function of cross correlation between the pressure at the wall of the collar (Fig. 1b) and flow velocities. The pressure signal was used as the reference signal in the correlation measurements. By comparing correlograms it was possible to determine the relative phase shifts between velocity oscillations at different points of the flow field. In this way the phase velocities were predicted.

Fig. 6 shows the correlation functions ($R_{up}$) mentioned above for three points in the outlet cross-section of the duct, whereas Fig. 7 gives $R_{up}$ for three

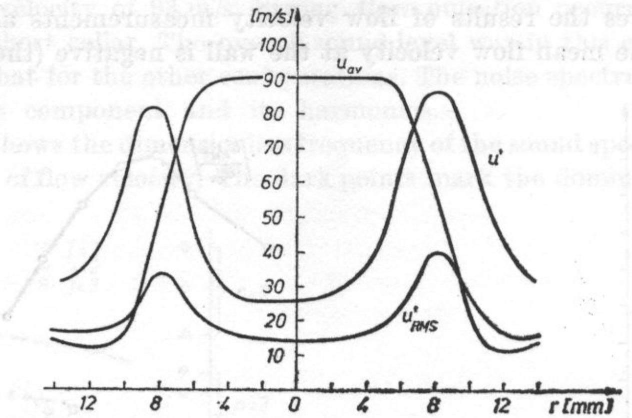


**Fig. 5. Velocity distributions in the outlet cross-section of the collar (notation as in Fig. 4)**

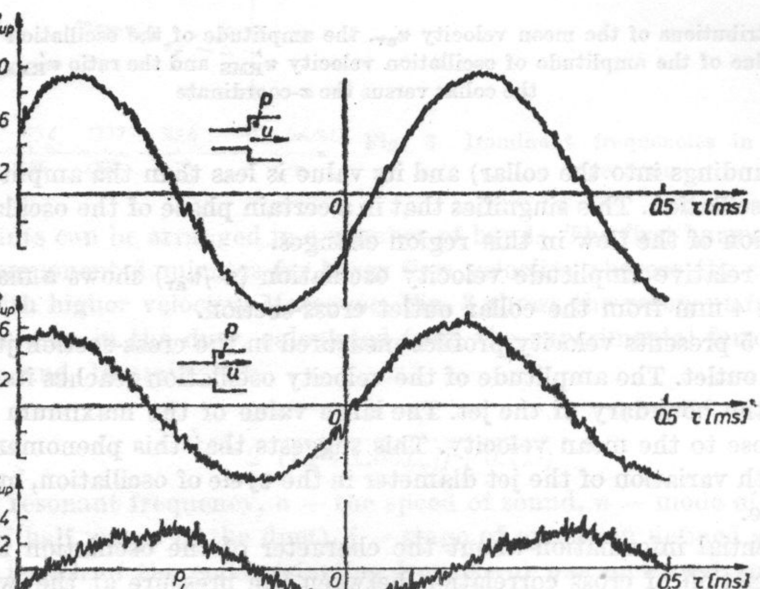


**Fig. 6. Correlograms of the pressure trace in the collar and velocity traces in the cross-section close to the outlet of the duct**

points in the outlet cross-section of the collar. At the axes of the abscissae of all these figures there are time delays ($\tau$) between correlated signals. The positive value of $\tau$ denotes the delay of the velocity signal with respect to the pressure signal.

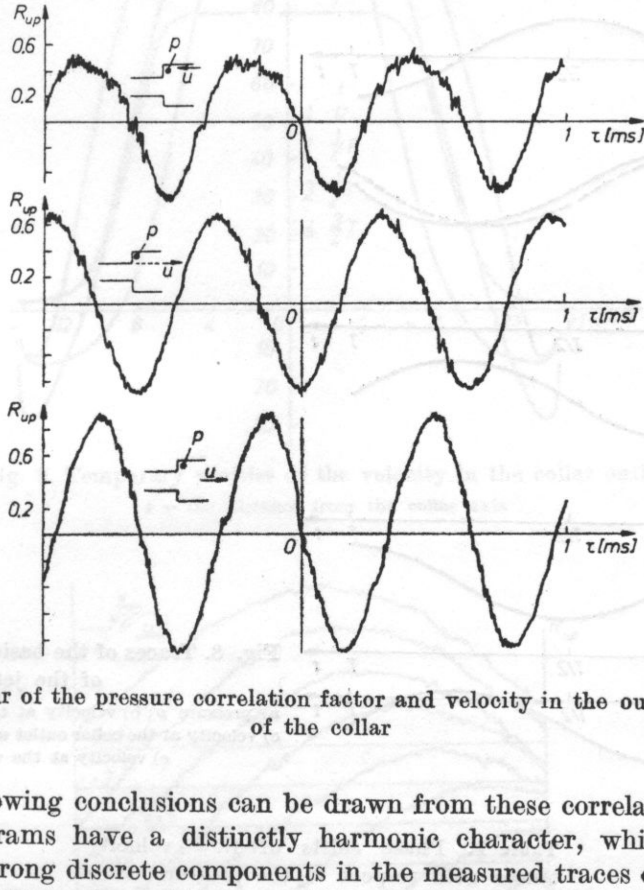


**Fig. 7. Behaviour of the pressure correlation factor and velocity in the outlet cross-section of the collar**

The following conclusions can be drawn from these correlation functions.

Correlograms have a distinctly harmonic character, which proves the existence of strong discrete components in the measured traces of the pressure and velocities. The values of the correlation functions are the greatest for velocities at the points along the axis of the duct. It indicates the least contribution of random components to this phenomenon. On the basis of the correlation functions the phase shifts between the basic flow parameters were found.

Fig. 8. shows the change in the main flow properties in one cycle of oscillation. All these lines were deduced from an analysis of the correlograms and velocity measurements. The approximate values of the phase shift between velocity signals at some points of the flow field and the reference pressure signal, corresponding to Fig. 8, are given in Table I. On the basis of the results of measurements given above, the temporary jet velocity profiles at the collar exit cross-section were also determined. These profiles are shown in Fig. 9. A $T/4$ phase shift between the velocity and jet diameter is clearly visible. It follows

from Fig. 9 that in this oscillation phase in which the flow velocity in the axis reaches its extreme values, the jet diameter is approximately the same as the duct diameter. However in the stages in which the flow velocity in the axis is close to the mean value, the jet diameter takes an extreme value.

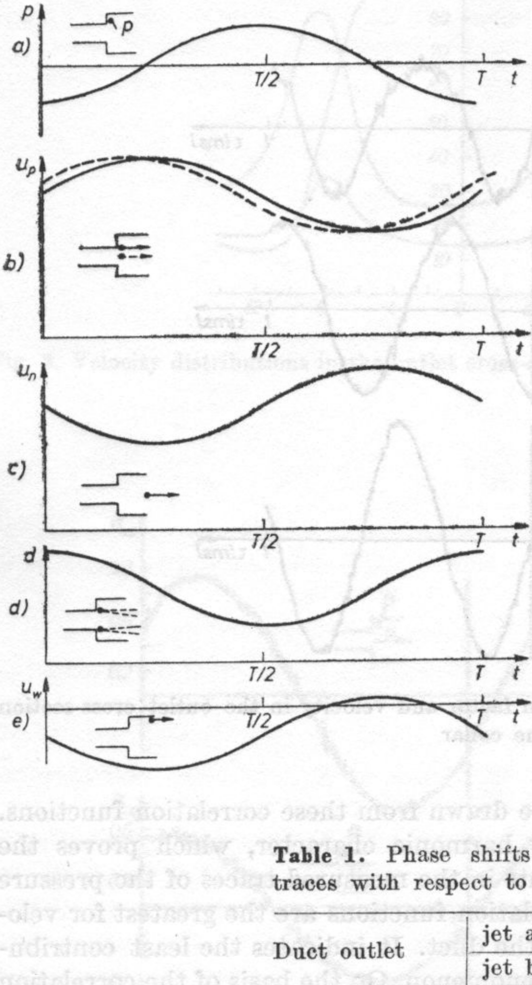


Fig. 8. Traces of the basic flow properties of the jet

a) pressure $p$; b) velocity at the duct outlet, $u_p$; c) velocity at the collar outlet $u_n$; d) jet diameter $d$; e) velocity at the wall, $u_w$

**Table 1.** Phase shifts of flow velocity traces with respect to the pressure trace

| | | |
|---|---|---|
| Duct outlet | jet axis | $^5/_8 T$ |
| | jet boundary | $^3/_4 T$ |
| Collar outlet | jet axis | $^1/_4 T$ |
| | jet boundary | $^1/_2 T$ |
| | wall | $^1/_4 T$ |

Fig. 10 shows a set of correlation functions for points along the axis of the jet. In Fig. 11 the phases with zero value of the correlation functions are arranged versus the position of the thermoanemometer probe. The inclination of a line represents the phase velocity. It follows from Fig. 11 that beyond the flow region close to the outlet of the duct the phase velocity is constant (50 m/s).

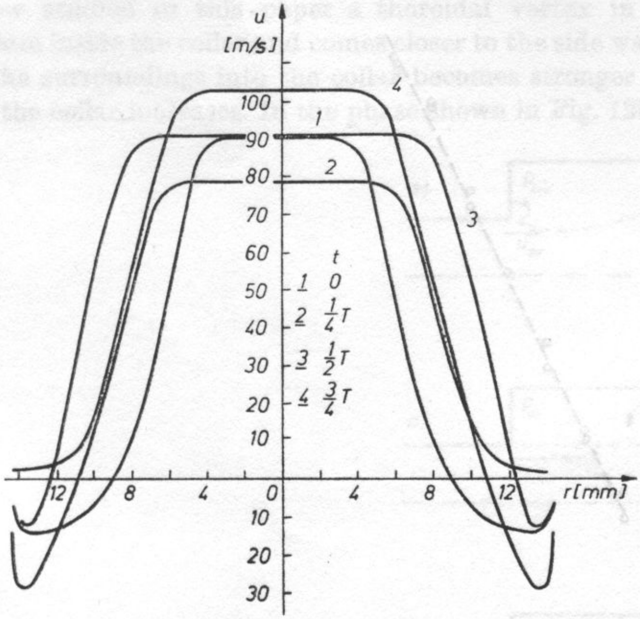


**Fig. 9. Temporary profiles of the velocity in the collar outlet**
**$r$ – the distance from the collar axis**

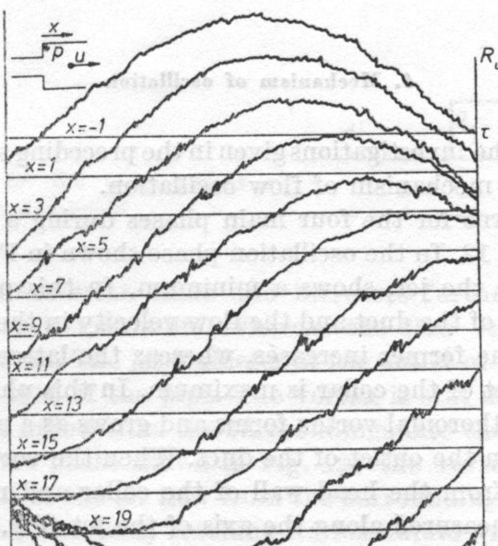


**Fig. 10. Set of correlograms for different positions of the thermoanemometer probe along the collar axis**

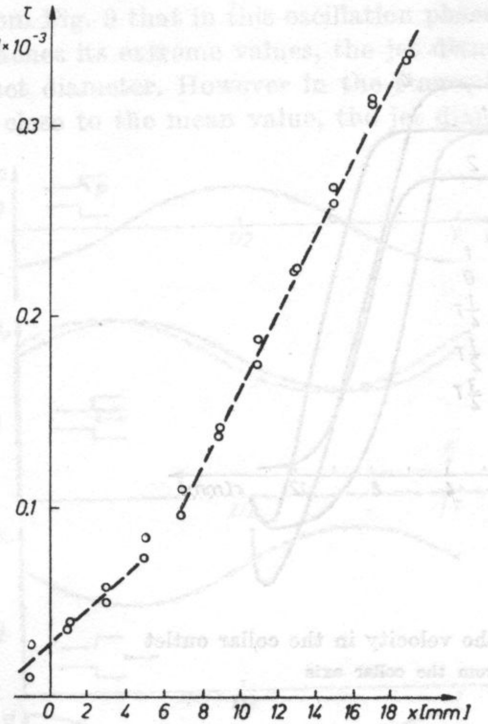


**Fig. 11. Positions of the phase surface for zero value of the correlation functions given in Fig. 10**

## 4. Mechanism of oscillation

The results of the investigations given in the preceding sections of this paper justify the following mechanism of flow oscillation.

The flow patterns for the four main phases during a cycle of oscillation are illustrated in Fig. 12. In the oscillation phase shown in Fig. 12a the pressure in the collar, outside the jet, shows a minimum. In this phase both the flow velocity in the outlet of the duct and the flow velocity in the outlet of the collar take mean values; the former increases, whereas the latter decreases. The jet diameter at the outlet of the collar is maximum. In this phase, or in a slightly ealier one, a distinct thoroidal vortex forms and grows as a result of an increase in the flow velocity in the outlet of the duct. When the vortex becomes strong enough it separates from the head wall of the collar and moves downstream. The phase velocity measured along the axis of the jet (Fig. 11) corresponds to the velocity of this vortex. It is about 0.6 of the mean flow velocity of the jet. This result confirms the observation given in paper [10] regarding the oscillation of a free jet impinging on a plate. In the oscillation discussed in [10] an important role is played by coherent vortices forming from smaller ones in the process of the so-called "collective interaction".

In the flow studied in this paper a thoroidal vortex in creases as it moves downstream inside the collar and comes closer to the side wall. As a result, the flow from the surroundings into the collar becomes stronger and therefore the pressure in the collar increases. In the phase shown in Fig. 12b the pressure

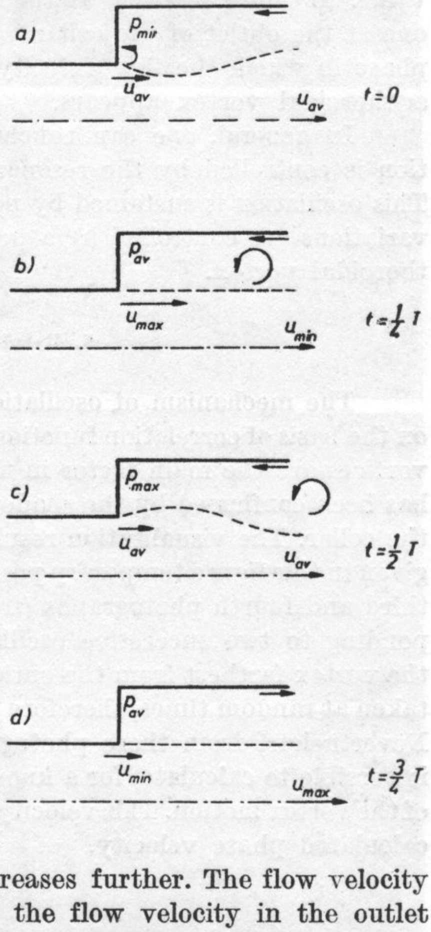


Fig. 12. Flow patterns for the main phases of the oscillation cycle

in the collar reaches the mean value and increases further. The flow velocity in the outlet of duct is maximum, whereas the flow velocity in the outlet of the collar is minimum. The jet diameter at the outlet of the collar is approximately the same as that of the pipe. The vortex is still inside the collar close to the outlet and the inflow from the surroundings into the collar is maximum.

In the successive phase shown in Fig. 12c the vortex is already outside the collar. As a result of the air flow from the surroundings into the collar, the pressure in the collar increases, reaching its maximum value higher than the surrounding pressure. (It was explained in section 3, on the basis of the results of velocity measurements, that in some oscillation phase the air flows along the walls into the surroundings. This indicates that there is overpressure in the collar). The flow velocities in the outlet of the duct and the outlet of the collar take mean values; the former decreases, whereas the latter increases.

The jet diameter at the outlet of the collar reaches its maximum value. In the further oscillation phase the pressure in the collar decreases as a result of the air outflow (along the walls) and of the jet ejection.

In the phase shown in Fig. 12 d the pressure in the collar has its mean value. The flow velocity at the outlet of the duct is minimum, whereas the one at the outlet of the collar is maximum. It is possible that already in this phase in which the flow velocity at the outlet of the duct starts to increase, a thoroidal vortex appears.

In general, one can conclude that the oscillation mechanism in question is controlled by the resonance oscillation of an air column in the duct. This oscillation is sustained by periodic pressure variations in the collar. These variations are controlled by a periodically appearing and downstream moving thoroidal vortex.

## 5. Results of flow visualisation

The mechanism of oscillation described above has been deduced mainly on the basis of correlation functions and velocity measurements. Strong thoroidal vortices are the main factor in this mechanism. The existence of the vortices has been confirmed by the shadow graph visualisation of a free stream outside the collar. The visualisation results are shown in Fig. 13. In the photographs given in this figure temporary positions of this vortex can be seen. In the second, third and fourth photographs (from top) one can observe two vortices corresponding to two successive oscillation cycles. As a result of flow turbulence, the vortex farthest from the outlet is partly distorted. These photographs were taken at random times, therefore the time intervals between them are unknown. Nevertheless, from these photographs in which two vortices can be seen, it is possible to calculate, for a known pulsation period, the approximate velocity of the vortex motion. This velocity is about 50 m/s and agrees with the previously calculated phase velocity.

## 6. Conclusions

The investigations reported on in this paper have confirmed the existence of strong oscillations in subsonic flow in a duct with a sudden cross-section increase. These oscillations are the source of an acoustic wave which increases the overall sound level generated by a jet by about 30 dB. The oscillation mechanism is controlled by the resonance oscillation of an air column in the duct. This oscillation is sustained by flow in the collar. These oscillations occur over a relatively wide range of variations in the flow velocity and collar length. One can suppose that the oscillation mechanism described above is not the only one. Preliminary investigations have shown some different flow patterns for higher flow velocities, which are now studied.

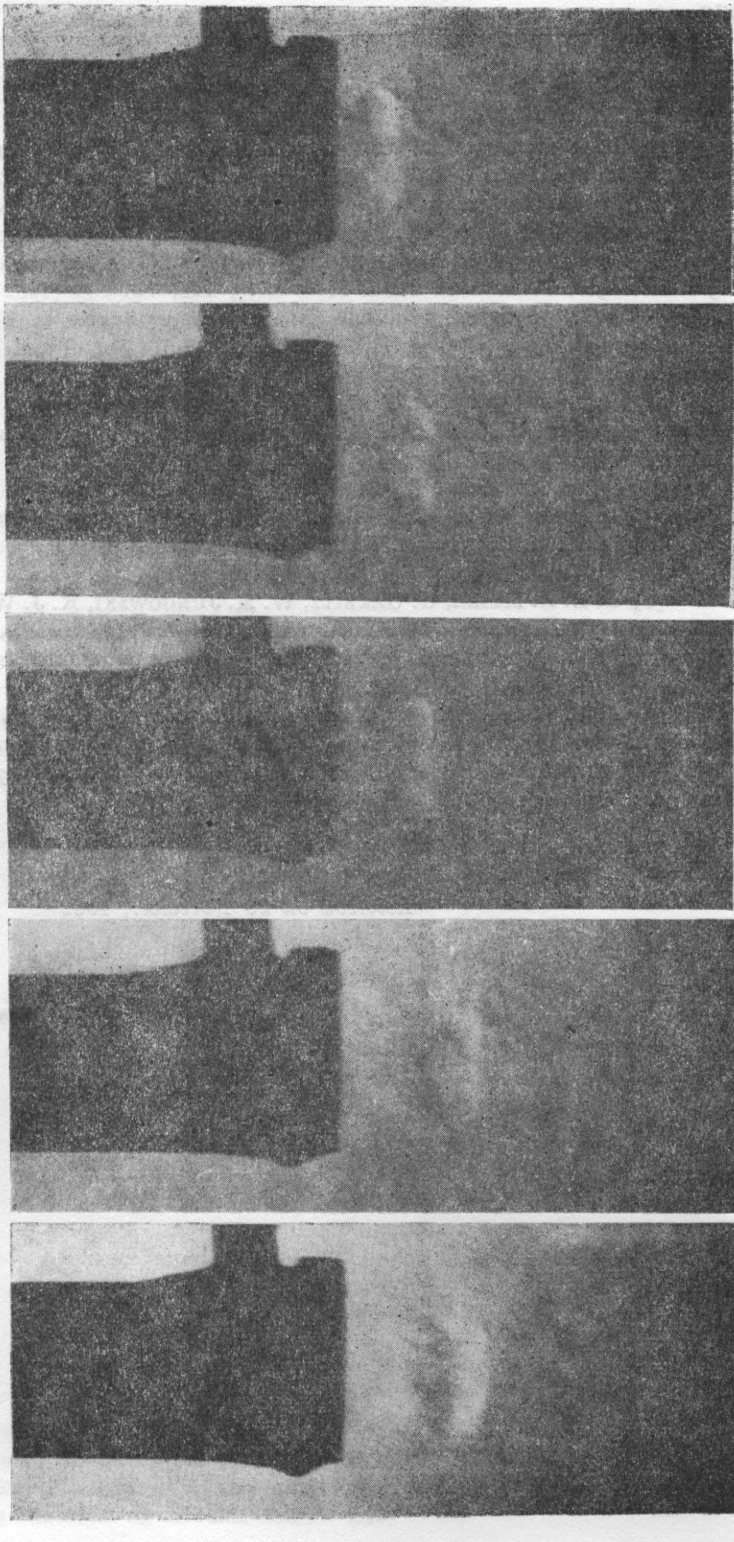

**Fig. 13. Photographs of the shadow graph visualisation of the free jet**

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