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FLOW PATTERNS AND NOISE OF A CHOKED GAS JET EXPANDING INTO A DUCT

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Axi-symmetric, choked air outflow into a duct with an abrupt enlargement of its cross-section was investigated in order to establish the relations between the flow pattern and the aerodynamic noise generated. Four main kinds of flow structure, possessing different acoustic properties, were found in the cases studied of the outflow from convergent circular and annular nozzles. These patterns correspond to the occurrence of: cellular structure, self-excited oscillations, single shock wave (noise minimum) and supersonic flow. An acoustic feedback type source of sound can appear under certain circumstances in the cellular structure. The self-excited shock wave and pressure oscillations produce noise characterized by discrete frequencies in the sound pressure level spectrum. The reasons for the minimum noise generation, which takes place before the reattachment of the supersonic stream boundary to the duct wall, are explained. Prevention of strong oscillations by the insertion of spoilers at the nozzle lip reduces the noise significantly over a wide range of supply pressures, however it increases the noise minimum due to turbulence intensity growth. Recommendations for nozzle and duct geometry for noise reduction are given.

1. Introduction

In high-pressure industrial installations the gas outflows from the slits of reducing valves and the inflows into ducts with an abrupt enlargement of their cross-section are predominantly choked. This means that the flow velocity at the nozzle exit is equal to the sound speed and an excess in gas pressure causes further jet expansion, the flow velocity in the duct thus attaining supersonic values.

Observation of installations shows that these flows can be a source of strong pressure oscillations and of high intensity noise with characteristic discrete frequencies in its spectrum. These are all unwanted and harmful effects, since the flow oscillations disturb technological processes, make the measurement of flow parameters difficult and produce mechanical vibrations. The noise, which accompanies them, causes the work circumstances for the operating personnel of such installations to be uncomfortable. For successful prevention of the flow oscillations a study of the phenomenon is necessary.

A survey of published work, connected with noise from choked gas outflows, showed that sound generation by free jets has been investigated rather thoroughly. However there are few papers devoted to outflows into a duct and they are not profound.

It is well known that in a subsonic free jet the most effective emitter of acoustic power is the mixing region, i.e. an intensely turbulent shear-layer between the central uniform jet core and the ambient air [1, 2, 3]. In supersonic flow, new sources of additional noise appear which begin to predominate over the turbulent mixing noise. A free choked gas jet possesses a cellular pattern, formed by expansion, compression and shock waves. The structure of cells and their dimensions depend on the difference between exit and ambient pressure levels.

The noise produced, due to the presence of cells in the stream, results from interactions between turbulent eddies or larger vortices and shock waves [1, 3, 4, 5]. It may be characterized by discrete frequencies in the spectrum, by acoustic feedback (*screech*), or as the noise produced by the same sources, but without feedback, being more broad-band but strongly peaked (*shock associated noise*) [4, 6].

The phenomenon of sound generation by vortex and shock wave interaction is not, as yet, fully explained. It is impossible to estimate theoretically the acoustic power of this type of source in the far field [6, 7].

The second kind of noise, which is characteristic of supersonic flows, takes the form of directional high frequency waves, the so-called Mach waves, emitted by eddies convected downstream on the jet boundary with a supersonic velocity in relation to the ambient sound speed [5, 8]. The source of these waves is located in the supersonic shear-layer near the nozzle.

The acoustic feedback type mechanism is the most effective of all the mechanisms responsible for generating aerodynamic noise. It has been shown that in this case the acoustic efficiency can be as high as 5% [9], whereas in the case of a uniform supersonic jet it does not exceed 0.6% [3]. The screech mechanism has been described by POWELL [10, 11, 12] in the following manner. Under favourable conditions, when the shear-layer on the jet boundary is most susceptible to loss of stability, the acoustic wave generated by the flow is capable of creating a vortex at the nozzle exit. This vortex is amplified in the stream and – when it passes through a shock wave – an acoustic pulse is emitted. Next, the acoustic wave disturbs the stability of the boundary layer at the nozzle exit and this is the source of a new vortex. Thus, the feedback loop is closed. For axi-symmetric screeching jets, the mode of vortices convected downstream is either toroidal [13, 14] or spiral [12, 13, 14]. Similar phenomena have been observed, when a choked gas jet impinges on a flat obstacle [15].

Investigations of the noise generated by flow in a duct have been mostly concerned with ejectors [16, 17], variable cross-section channels [18, 19] and reducing valves [20, 21, 22, 23].

The emission of discrete frequency sound with acoustic feedback was found with a choked outflow from an ejector nozzle [16], just as for free jet. Studies on the axi-symmetric air outflow from a convergent nozzle into a duct with an abrupt enlargement of its cross-section revealed [18, 19] two sources of the discrete frequency noise: one associated with the cellular flow structure, and the second occurring when the normal shock wave was present in the duct. On the basis of the work of JUNGOWSKI [24, 25, 26] and the present author [27], it seems that strong self-excited oscillations of pressure in the dead-air region, accompanied by shock wave oscillations, give rise to the second source of noise. Reports relating to the study of reducing valve noise, contain experimental data about the acoustic power and efficiency of different valve types, and discuss constructional modifications used to attempt to decrease the generated noise level. In order to split the mixing region of the stream outflowing from the valve slit, perforated plates [23] or throttling labyrinths [20] are most often placed at the low-pressure side.

In the investigations of axi-symmetric choked gas outflow into a duct with an abrupt enlargement of its cross-section decribed below, the author was guided by necessity to establish the relationship between the flow pattern and the aerodynamic noise generated. Knowlegde of this relationship should permit such designing of the channels of installations as to lead to a decrease in the acoustic power level emitted.

Notation

AP	amplitude in spectrum of pressure oscillation
D	duct diameter
d	nozzle diameter
d_c	central body diameter of annular nozzle
f	frequency
$OSPL$	overall sound pressure level in [dB] $\Delta OSPL = OSPL - OSPL^*$ [dB]
p	pressure $\overline{p} = p/p_0$, $\overline{p}_0 = p_0/p_0^*$
Δp	double amplitude of pressure oscillation
SPL	sound pressure level in [dB] $\Delta SPL = SPL_f - OSPL$ [dB]
φ	ratio of nozzle area to duct area

Suffixes

c	central dead-air region
f	at definite frequency
o	supply
w	outer dead-air region
$*$	appearance of critical outflow from nozzle

2. Outline of experimental studies and measuring technique

The axi-symmetric air outflow from a convergent circular or annular nozzle into a duct with an abrupt enlargement of its cross-section (Fig. 1) was investigated experimentally. The annular nozzle can be regarded as an approximate model of reducing valve. High-pressure air was fed to the supply chamber (1) and the test section (2) was connected with the atmosphere through the set of outlet ducts.

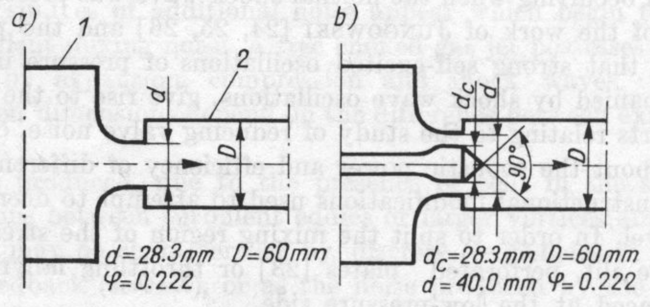

Fig. 1. Circular (a) and annular (b) nozzle arrangements investigated
1 — supply chamber, *2* — test section

The *OSPL* measurements and the spectral-analysis were performed using Brüel and Kjaer equipment. A half-inch microphone was placed in the free field outside the duct, at a distance of 0.4 m away from its axis. Since it was found that the character of the spectra in the neighbourhood of the test section are subject only to minor changes, a representative microphone location was assumed to be a point in the horizontal plane at the height of the duct axis. The microphone was placed at an angle of 45° to the duct axis, and directed towards the nozzle exit, near to which the most powerful sources of noise are located.

The flow patterns were investigated by measurement of: the static pressure distribution along the duct; traces of the oscillating pressure and their associated spectra; flow visualization using schlieren and shadowgraph methods; and streak-pictures (*x-t* plane). In order to make even a partial visualization possible, a portion of the duct wall, equal in width to half of the diameter, was removed and replaced by flat windows made from optical glass.

3. Flow patterns

The diagrams in Fig. 2 show the nondimensional pressure in dead-air regions downstream of the circular (a) and annular (b) nozzles versus the nondimensional supply pressure, starting from the beginning of critical outflow. In the range of decreasing $\overline{p}_w$ the subsonic stream boundary reattaches to the

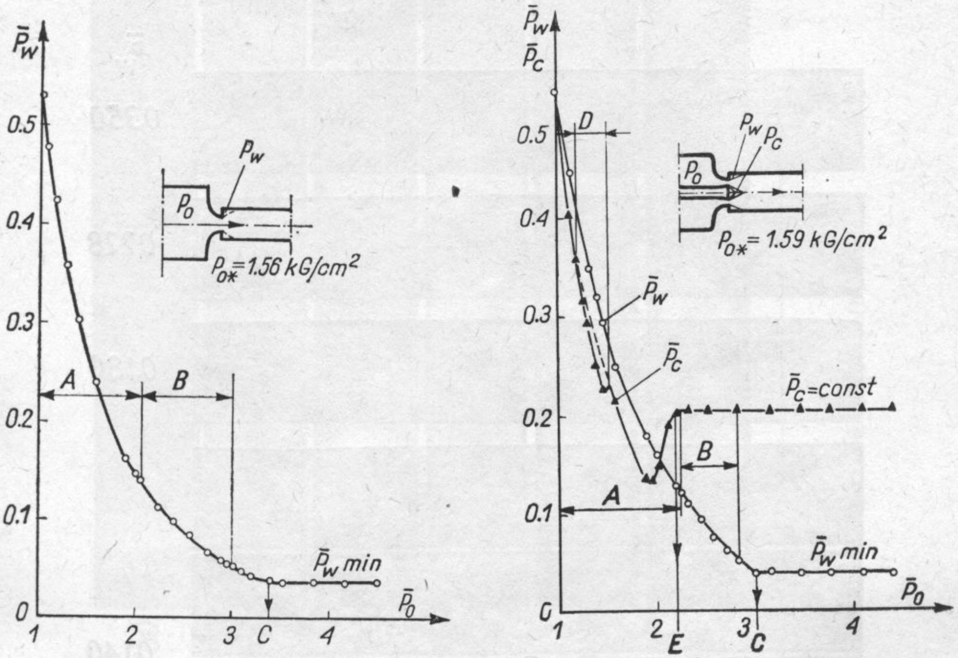

Fig. 2. Nondimensional pressure in outer ($\bar{p}_w$) and central ($\bar{p}_c$) dead-air region versus nondimensional supply pressure ($\bar{p}_0$); choked outflow from circular (a) and annular (b) nozzle into the duct

A – cellular structure, B – self-excited oscillations, C – supersonic reattachment, D – oscillations with acoustic feedback, E – closed central dead-air region

duct wall (the so-called *subsonic reattachment*). When the supersonic stream boundary isolates the dead-air region and $\bar{p}_0$ increases, $\bar{p}_w$ maintains its minimum constant value (the so-called *supersonic reattachment*).

At first the flow possesses the features of an underexpanded free jet. The dead-air region is large, since the subsonic stream boundary reattaches to the duct wall a long distance away from the nozzle. The photographs in Fig. 3 and 4a ($\bar{p}_w = 0.350$-0.180) show the cellular structure of the supersonic region downstream of the circular nozzle, and the photographs in Fig. 4b ($\bar{p}_w = 0.400$-0.180) show the annular form of the cells in the flow downstream of the annular nozzle.

As the supply pressure further increases, self-excited flow oscillations occur, which are characterized by cyclic variations in flow pattern connected with oscillation of the shock waves and the reattachment zone. Figure 3, for example, shows the changes in flow pattern from a cellular structure to a single shock wave with a frequency of 180 Hz ($\bar{p}_w = 0.140$), and the changes in shape and position of a single shock wave in the flow oscillating with a frequency of 560 Hz ($\bar{p}_w = 0.066$).

After the decay of the self-excited flow oscillations ($\bar{p}_w = 0.046$), before supersonic reattachment, downstream of the single bulging shock wave, near

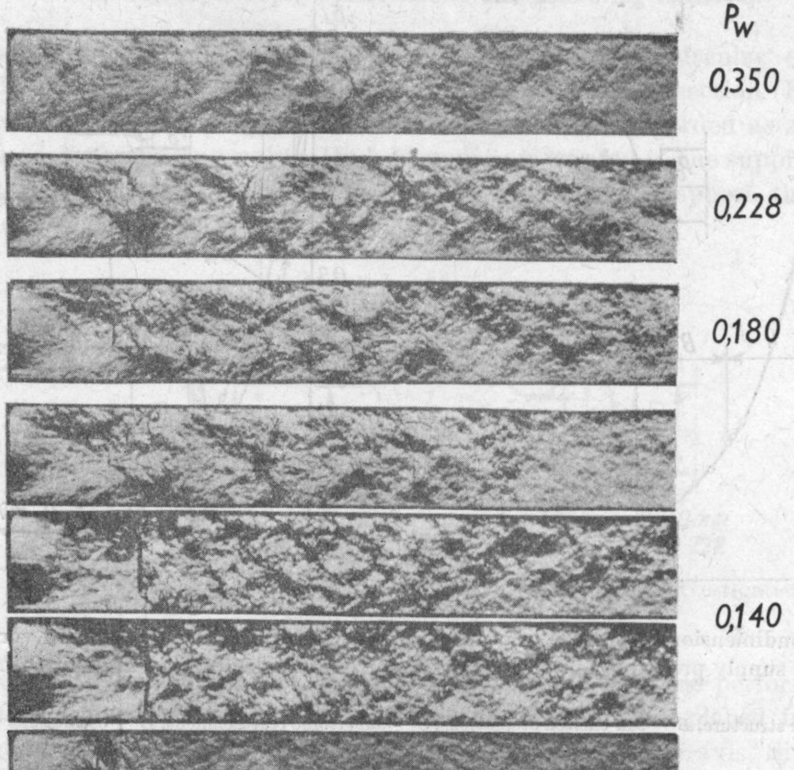

Fig. 3. Schlieren visualization of flow downstream of circular nozzle

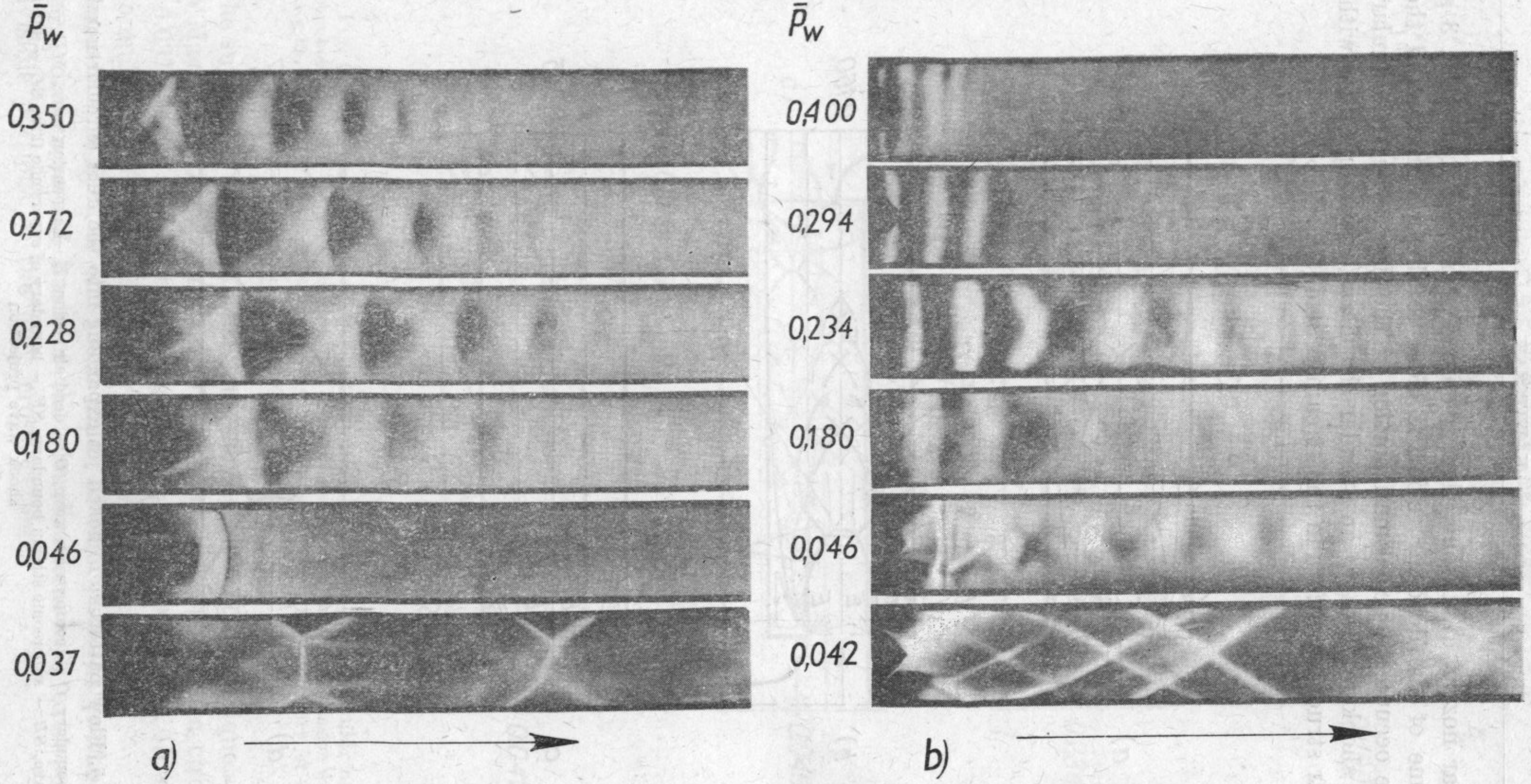

Fig. 4. Schlieren visualization of flow downstream of circular (a) and annular (b) nozzle

the circular nozzle, a subsonic flow is spread along the duct (Fig. 3 and 4a). The volume of the dead-air region is close to the minimum, and the supersonic zone occupies a very small portion of the duct. For the annular nozzle, the single shock wave takes an annular shape and supersonic flow with a typical cellular structure occurs in the stream centre (Fig. 4a).

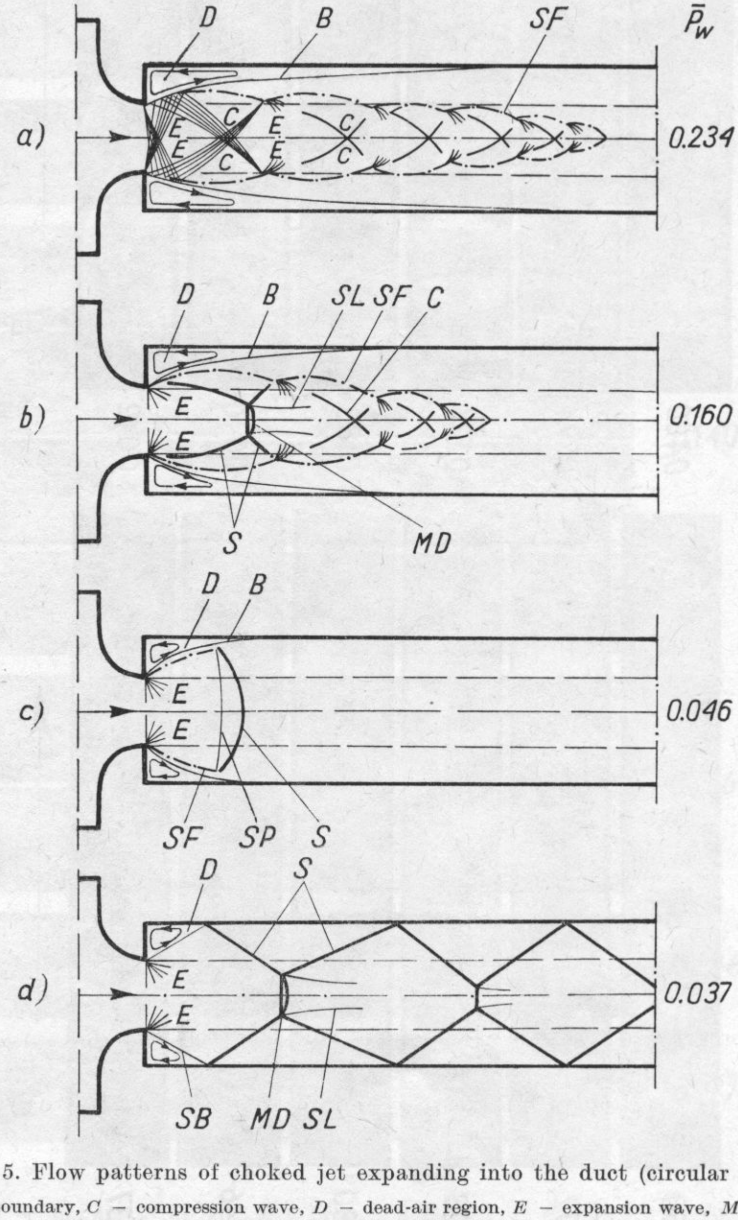

Fig. 5. Flow patterns of choked jet expanding into the duct (circular nozzle)

B – stream boundary, C – compression wave, D – dead-air region, E – expansion wave, MD – Mach disk, S – shock wave, SB – supersonic stream boundary, SF – boundary of supersonic flow, SL – slip line, SP – shock wave projection

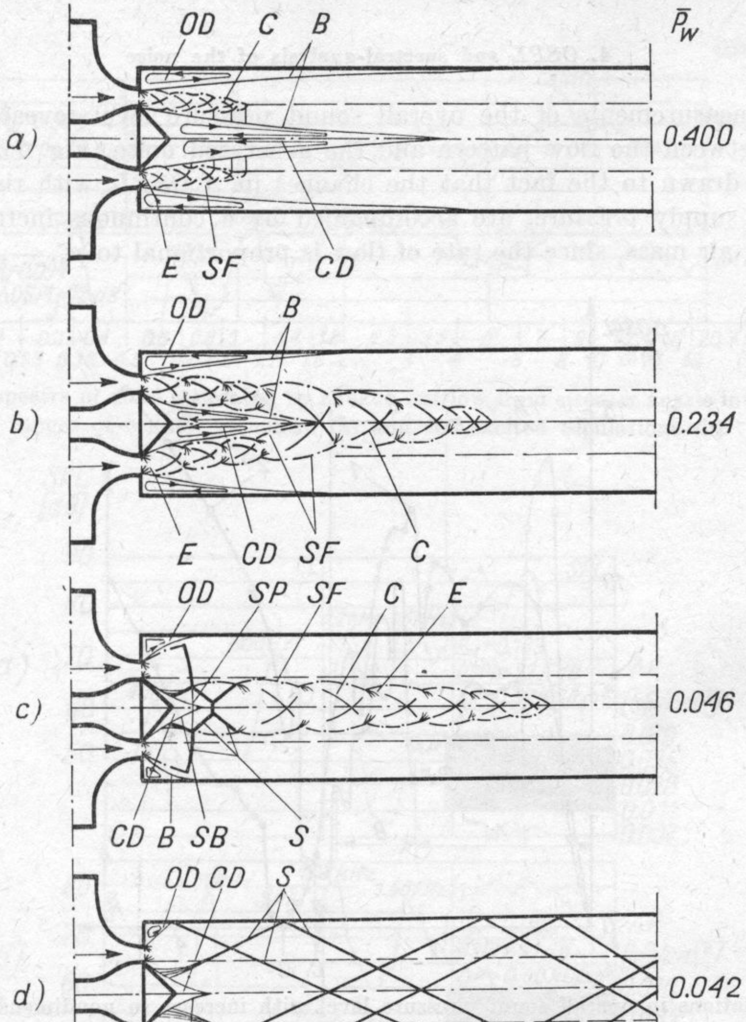

Fig. 6. Flow patterns of choked jet expanding into the duct (annular nozzle)
B – stream boundary, C – compression wave, CD – central dead-air region, E – expansion wave, OD – outer dead-air region, S – shock wave, supersonic stream boundary, SF – boundary of supersonic flow, SP – shock wave projection

The supersonic reattachment causes the occurrence of oblique shock waves with a Mach disk (Figs. 3 and 4a) in the flow downstream of a circular nozzle ($\overline{p}_w = 0.037$), and a set of intersecting oblique shock waves (Fig. 4b) downstream of an annular nozzle ($\overline{p}_w = 0.042$).

Figures 5 and 6 show the main kinds of flow patterns (without unstable processes) drawn on the basis of the visualization, with extrapolation over the invisible portions of the duct cross-section.

4. *OSPL* and spectral-analysis of the noise

The measurements of the overall sound pressure level revealed a strict relation between the flow pattern and the generated noise (Fig. 7). Attention should be drawn to the fact that the changes in *Δ OSPL*, with rising nondimensional supply pressure, are accompanied by a continuous increase in the outflowing air mass, since the rate of flow is proportional to p_o.

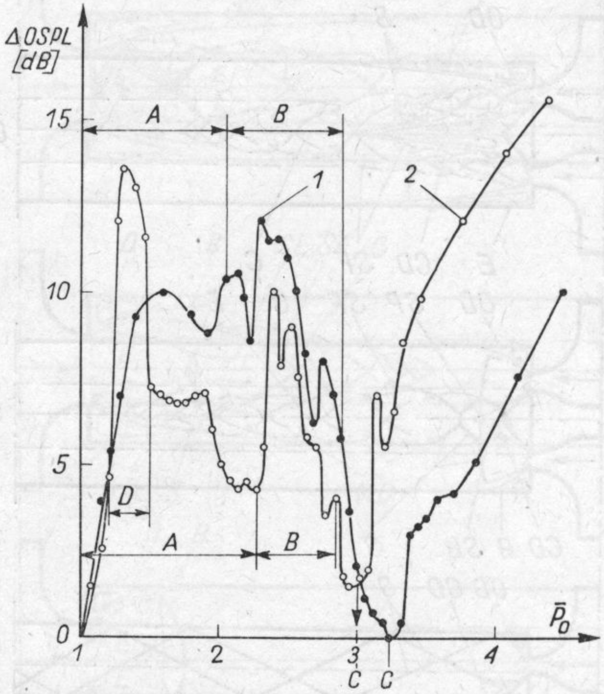

Fig. 7. Variations in overall sound pressure level with increase in nondimensional supply pressure; choked outflow from circular (*1*) and annular (*2*) nozzle into the duct
A – cellular structure, *B* – self-excited oscillations, *C* – supersonic reattachment, *D* – oscillations with acoustic feedback

Starting from the occurrence of the critical conditions at the nozzle exit, in the range of the cellular structure, the noise level increases – in the beginning almost linearly – and then this increase stops. The strong noise maximum ($\bar{p}_0 \approx 1.3$) in the case of the outflow from an annular nozzle is related to the appearance of the particularly effective (acoustic feedback) source of sound with discrete frequencies (3.2 and 6.4 kHz in the spectrum in Fig. 14a). This type source was not observed in the flow downstream of the circular nozzle, but the peak in the spectrum at about 7.3 kHz (Fig. 8a) indicates the sound generated by the interaction of flow disturbances and shock waves.

When the shock waves in the first cell become stronger (Mach disk), the noise diminishes and only self-excited flow oscillations cause an increase

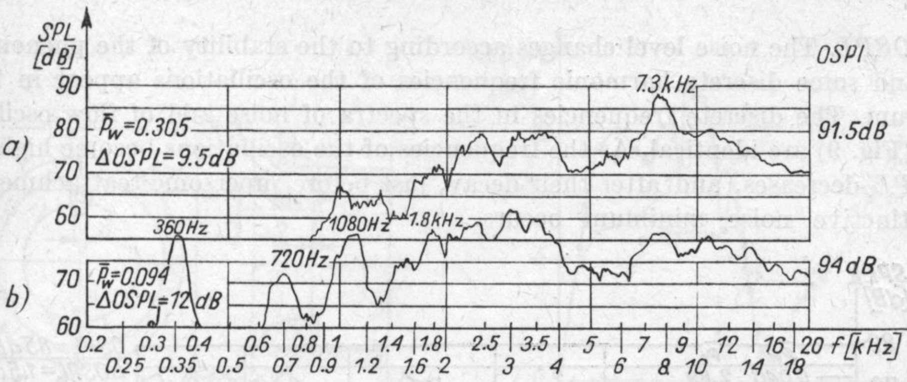

Fig. 8. *SPL* spectra of noise generated by choked outflow from circular nozzle into the duct; ranges of cellular structure (a) and self-excited oscillations (b)

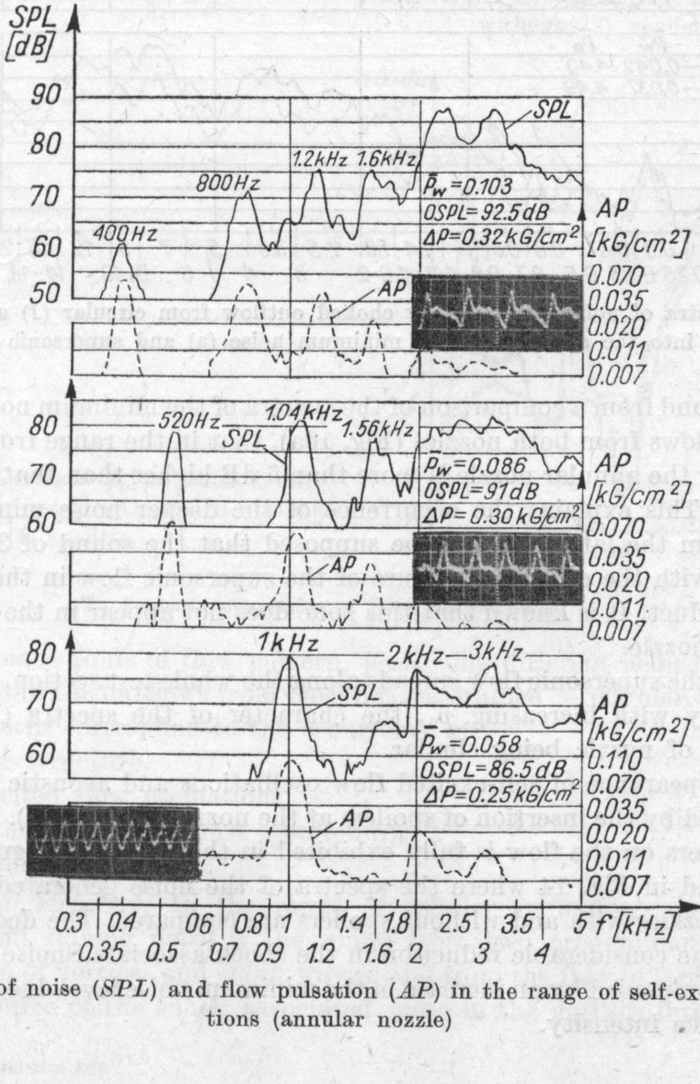

Fig. 9. Spectra of noise (*SPL*) and flow pulsation (*AP*) in the range of self-excited oscillations (annular nozzle)

in *Δ OSPL*. The noise level changes according to the stability of the phenomenon and some discrete harmonic frequencies of the oscillations appear in the spectrum. The discrete frequencies in the spectra of noise and of flow oscillations (Fig. 9) are identical. As the frequencies of the oscillations become higher, *Δ OSPL* decreases, and after their decay, just before supersonic reattachment, a distinctive noise minimum occurs.

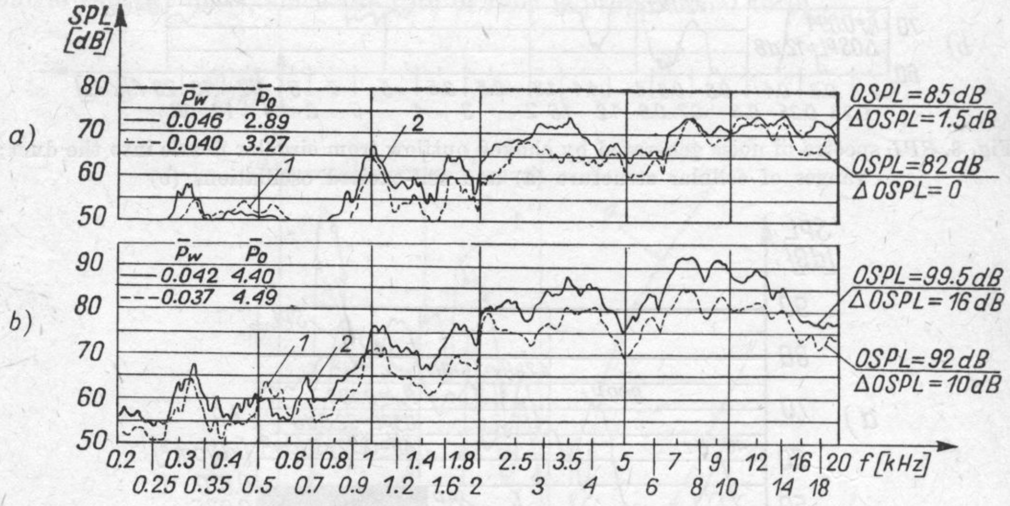

Fig. 10. Spectra of noise generated by choked outflow from circular (*1*) and annular (*2*) nozzle into the duct; ranges of minimum noise (a) and supersonic flow (b)

It is found from a comparison of the spectra of the minimum noise, generated by the outflows from both nozzles (Fig. 10a), that in the range from 3 to 4 kHz the ***SPL*** for the annular nozzle is more than 5 dB higher than that for the circular nozzle. This explains the occurrence of the deeper noise minimum at the outflow from the latter. It may be supposed that the sound of 3 – 4 kHz is connected with the cellular structure of the supersonic flow in the central portion of the duct. It is known that this zone does not appear in the outflow from a circular nozzle.

When the supersonic flow spreads along the whole test section, *Δ OSPL* rises continuously with increasing $\bar{p}_0$, the character of the spectra (Fig. 10b) for both types of nozzle being similar.

The appearance of self-excited flow oscillations and acoustic feedback can be prevented by the insertion of spoilers at the nozzle lip (Fig. 11). The influence of the spoilers on the flow is fully exhibited in the ***Δ OSPL*** diagrams (Figs. 12 and 13), and in Fig. 14 where the spectra of the noise generated by outflows from the nozzles with and without spoilers are compared. The decay of oscillations and the considerable reduction in the shock associated noise are, unfortunately, accompanied by an increase in the minimum noise level due to the growth of turbulence intensity.

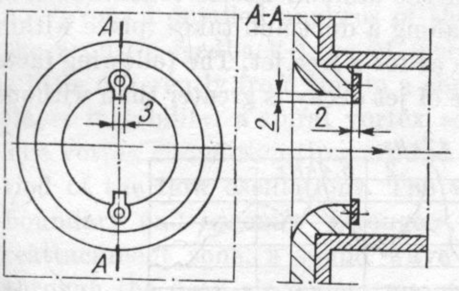

Fig. 11. Dimensions and arrangement of spoilers at nozzle lip

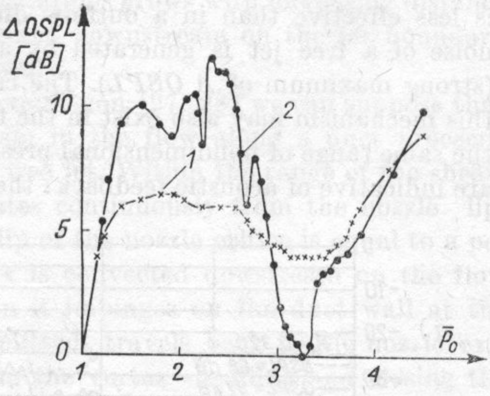

Fig. 12. $\Delta\, OSPL$ versus $\bar{p}_o$ for choked outflow from circular nozzle with (*1*) and without (*2*) spoilers

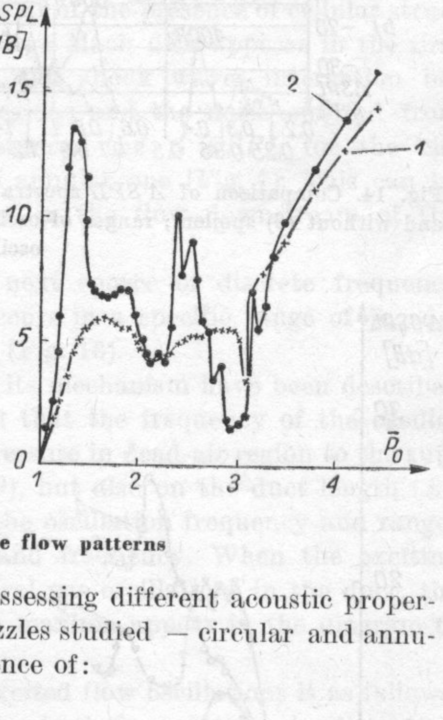

Fig. 13. $\Delta\, OSPL$ versus $\bar{p}_o$ for choked outflow from annular nozzle with (*1*) and without (*2*) spoilers

5. Acoustic properties of the flow patterns

The four main kinds of flow pattern, possessing different acoustic properties, were found in the outflows from both nozzles studied — circular and annular. These patterns correspond to the occurrence of:

(a) cellular structure,
(b) self-excited flow oscillations,
(c) single shock wave (noise minimum),
(d) supersonic flow.

5.1. *Cellular structure.* In the range of cellular structure, superimposed on the turbulent mixing noise is the sound from two predominant sources: from interaction of vortices and shock waves, and from the flow in large dead-air regions. The source of the shock associated noise in the outflow into the duct is less effective than in a outflow directly to the atmosphere (Fig. 15). The noise of a free jet is generated by an acoustic feedback type of mechanism (strong maximum of *Δ OSPL*). The case of the annular nozzle confirmed that this mechanism may also exist in the flow along a duct and takes place within the same range of nondimensional pressures as for a free jet. The following facts are indicative of acoustic feedback: the rate of jet decay is greater than without

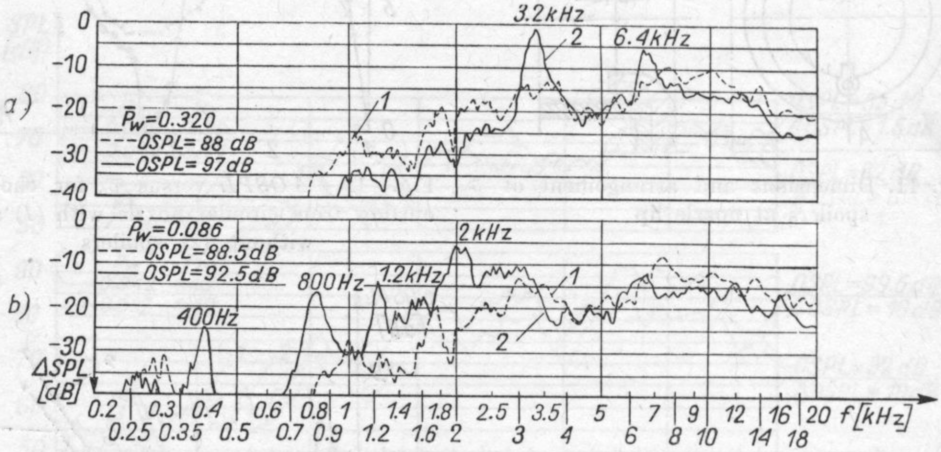

Fig. 14. Comparison of *Δ SPL* spectra for choked outflow from annular nozzle with (*1*) and without (*2*) spoilers; ranges of oscillations with acoustic feedback (a) and self-excited oscillations (b)

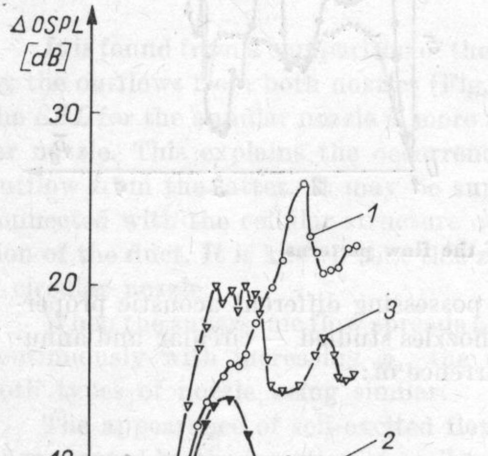

Fig. 15. Comparison of *Δ OSPL* versus $\bar{p}_w$ for free jets and outflows into duct

Circular nozzle: free jet (*1*), outflow into duct (*2*), annular nozzle: free jet (*3*), outflow into duct (*4*) oscillations, the amplitude of the flow oscillations grows with increasing distance from the nozzle, disturbances are convected downstream on the jet boundary and decay after impinging on the duct wall.

From a detailed analysis of the phenomenon [27, 28] we can suppose that the acoustic feedback type of mechanism in the flow along a duct proceeds a little differently from this in a choked free jet. Within the range of the shear-layer instability, a spiral vortex separates continuously from the nozzle lip. The vortex circulation-time around the lip of the nozzle orifice is equal to a period of the flow oscillations. The vortex is convected dowstream on the flow boundary and becomes stronger. When it impinges on the duct wall at the reattachment zone, a sound wave is emitted, travels back to the nozzle exit through the dead-air region, maintaining the vortex shedding and closing the feedback loop.

The mechanism described above is rather similar to the situation when a choked gas jet impinges on an obstacle [15].

At a value of $\overline{p}_w$ corresponding to the end of the presence of cellular structure, when a shock wave pattern with a large Mach disk appears in the first cell, Δ *OSPL* diminishes, since the vortex and shock waves interaction becomes weaker. In addition, the dead-air regions and the noise emitted from them are reduced. Under these circumstances the Δ *OSPL* for the circular nozzle is a little higher than for the annular one (Fig. 7). This can be explained by the shorter supersonic region in the flow downstream of the latter nozzle.

5.2. *Self-excited flow oscillations.* The next source of discrete frequency noise – self-excited flow oscillations – occurs in a specific range of $\overline{p}_w$, depending on φ, in the neighbourhood of $\overline{p}w_{\min}$ (Fig. 16).

Investigations of the phenomenon and its mechanism have been described in detail elsewhere [27]. It was established that the frequency of the oscillations depends not only on the ratio of the pressure in dead-air region to the supply pressure ($\overline{p}_w$) and the duct diameter (D), but also on the duct length (L). Among others, we find sudden changes in the oscillation frequency and ranges of evident instability of both amplitude and frequency. When the exciting frequency is close to the frequency of natural gas oscillations in the duct, the flow oscillations are amplified. In this case maxima appear in the diagram of Δ *OSPL* versus $\overline{p}_0$.

The essence of the mechanism of self-excited flow oscillations is as follows. Under some conditions the equilibrium of the dead-air region can be disturbed, i.e. the mass flow ejected from the dead-air region ceases to be equal to the mass flow reversed back into it from the reattachment zone. The flow separates from the duct wall, and changes in the magnitude of the dead-air region and shock wave oscillation occur. The time-varying effects in the dead-air region vary the boundary conditions of the main flow and this results in a fluctuation of flow parameters. The dead-air region and main flow interaction is delayed

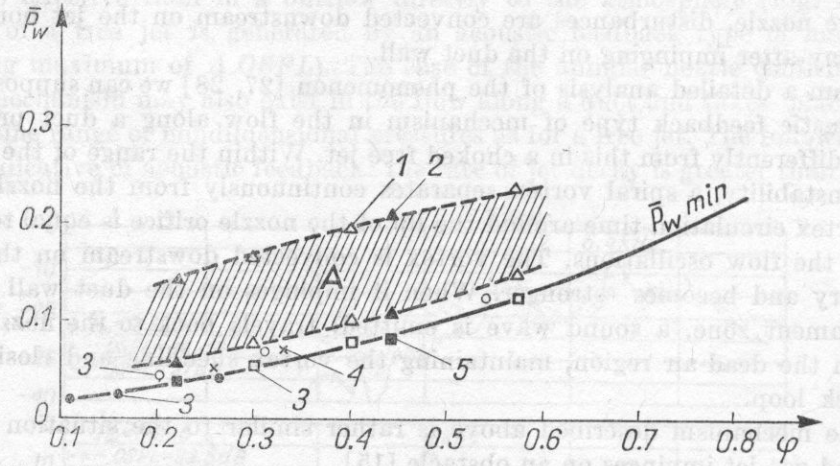

Fig. 16. Experimental values of $\bar{p}_w$ for range of self-excited oscillations and for supersonic reattachment ($\bar{p}_{w_{\min}}$)

A — range of self-excited oscillations, *1* — from [25], *2* — from [27], $p_{w_{\min}}$, *3* — from [25], *4* — from [18, 19], *5* — from [27]

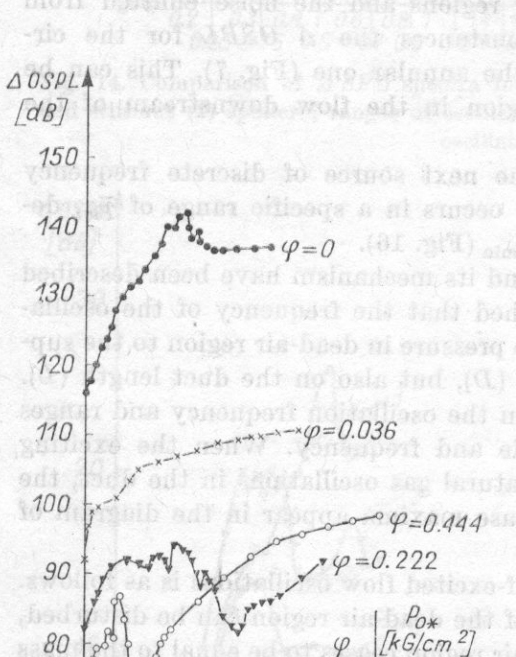

Fig. 17. Comparison of *OSPL* versus $\bar{p}_0$ for outflows from circular nozzle into various φ ducts and to the atmosphere (φ = 0)

due to inertial effects (for instance — the upstream motion of compression or expansion waves) preventing the formation of equilibrium between these two regions and maintaining unsteady processes.

When the self-excited flow oscillations appear, the low frequency sound — in a range of frequencies up to about 3 kHz — contributes more to the noise spectrum (Fig. 14b).

With a rise in the supply pressure the frequencies of oscillations increase, while changes in the flow pattern become weaker. Thus the amplitudes of oscillations diminish and, moreover, the dead-air region and the zone of supersonic flow are contracted. Owing to the influence of all these factors the $\Delta\, OSPL$ displays a tendency to reduce.

5.3. *Single shock wave* (*noise minimum*). The most advantageous flow pattern — from the point of view of the noise generation — occurs in the duct after the decay of self-excited oscillations. It is evident from Fig. 7 that the reduction in $\Delta\, OSPL$ in the case of a circular nozzle is very strong, because it reaches — in spite of an almost triple increase in the mass rate of flow — the level recorded at the beginning of critical outflow from the nozzle. The noise minimum appears as a result of a considerable flow velocity reduction due to the presence of a single shock wave near the circular nozzle. In these circumstances, the noise spectrum represents, in fact, the broad-band noise of turbulent subsonic flow along the duct, because the supersonic region is minimal.

The minimum noise level for the annular nozzle is 1.5 dB higher than for the circular nozzle owing to the fact that the shape of shock wave is annular and supersonic flow occupies the central portion of the duct.

A flow structure with similar acoustic properties (noise minimum) was obtained as a result of the interaction of two co-axial supersonic jets — circular and annular [29]. Its characteristic feature was also a minimal supersonic region due to the formation of a shock wave pattern near the nozzle in both jets. It was estimated that the contribution of the supersonic region to the emission of acoustic power was less than 1 %, almost all the noise being generated by the subsonic mixing region of the jets.

5.4. *Supersonic flow*. When the supersonic stream boundary reattaches itself to the wall, supersonic flow with a system of oblique shock waves appears in the duct. The supersonic region spreads downstream along the duct as the supply pressure grows, but the Mach number on the stream boundary and the flow pattern near the nozzle remain unchanged. The noise in this range increases continuously. The difference between the $\Delta\, OSPL$ levels (Fig. 7) just after the supersonic reattachment, can be explained by some dissimilarity of the flow structures downstream of the nozzles. The shock wave pattern in the case of the circular nozzle exhibits Mach disks, thus in a small region the flow is subsonic. On the other hand, downstream of the annular nozzle the set of intersecting oblique shock waves is doubled; shocks are formed in the reattachment zone at the duct wall and at the boundary of the central dead-air region in the place where the flow direction is changed. The progressive rise in Δ *OSPL* is, however, similar for both nozzles.

6. Conclusions

The noise generated by choked gas outflow into a duct with an abrupt enlargement of its cross-section is closely connected with the type of flow pattern. As the supply pressure grows, cellular structure, self-excited flow oscillations, single shock wave and supersonic flow occur consecutively in the duct downstream of the nozzle.

In the flow along the duct acoustic feedback can appear, but it is impeded and less effective than in a free jet, its mechanism differing a little from the «screech» mechanism. In order to fully understand the phenomenon of acoustic feedback in the flow along the duct, the conditions necessary for its presence should be established. We can suppose that since the vortex has to impinge on the duct wall under favourable circumstances in order to emit an acoustic wave, which closes the feedback loop, this phenomenon cannot appear for both small and large φ. In the first case, the vortex decays before arriving at the wall, and in the second case it impinges on the duct wall before it has been appropriately amplified.

The investigations performed revealed that flow oscillations — of both acoustic feedback and self-excited types — are the most effective noise sources in the range of $\bar{p}_w$ up to supersonic reattachment. The discrete frequencies in the spectra of the noise generated, when these two types of oscillations are present, agree completely with the frequencies of pressure oscillations in the flow. Under such circumstances a spectral analysis of the sound recorded in the free field outside the duct could be helpful in determining the frequencies of the flow oscillations.

The most favourable flow circumstances, characterized by the emission of minimum acoustic power, occur in the duct just before supersonic reattachment, when the single shock wave near the nozzle causes a considerable reduction in flow velocity.

The insertion of spoilers at the nozzle exit prevents strong flow oscillations, diminishing the noise in a wide range of supply pressures. It does, however, increase its minimum value before supersonic reattachment due to the growth of turbulence intensity.

The main conclusions of practical significance to be drawn from this work, are as follows.

The more the outflow into the duct is similar to a free jet (small values of φ), the stronger is the shock associated noise and the noise emitted from the dead-air region.

For a high φ the supersonic stream boundary reattaches to the duct wall at a low supply pressure. In view of the noise generation supersonic flow along the duct is undesired.

In the case of devices having little change of supply pressure, the geometrical dimensions of the nozzle and the duct should be chosen in such a way that the operating conditions correspond to the noise minimum. These conditions can easily be established since they occur just before $\overline{p}w_{\min}$. It is more purposeful to select the lower values of φ, e.g. of the order of 0.2 to 0.3, because the range of the noise minimum is wider for these values and, moreover, because the appearance of supersonic reattachment requires a higher change in the supply pressure.

If the supply pressure of the installation is varied over a wide range, the ratio of the nozzle area to the duct area should be so selected that $\overline{p}w_{\min}$, and thus supersonic flow along the duct, are avoided. Strong flow oscillations can be prevented by the insertion of spoilers at the nozzle exit. In this case, the device is characterized by an almost constant noise level, in spite of large changes in the supply pressure.

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