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Properties of an annular jet generating discrete frequency noise

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INVESTIGATING a choked air outflow from annular nozzle into a duct the authors found that at some level of supply pressure radiated noise was extremely strong and discrete frequencies appeared in spectrum. On the basis of: static pressure distribution, measurements of pressure oscillations, flow visualisation by schlieren, streak-picture (x-t), overall sound pressure level and spectrum-analysis of noise, the pattern of flow was studied and the mechanism of phenomena described.

Badając krytyczny dławiony wypływ powietrza dyszą pierścieniową do przewodu, autorzy stwierdzili, że w pewnym zakresie ciśnień zasilania wytwarzany hałas jest szczególnie silny, a w widmie występują dyskretne częstotliwości. Na podstawie rozkładu ciśnień statycznych, pomiaru ciśnień pulsujących, wizualizacji przepływu metodą smug, obrazów przepływu na płaszczyźnie x-t oraz pomiaru natężenia i widm hałasu, zbadano strukturę przepływu i opisano mechanizm zachodzących zjawisk.

При исследовании недорасширенного истечения воздуха из кольцевого звукового сопла в трубу авторы заметили, что в некотором диапазоне давления в форкамере излучаемый шум очень интенсивный, а в спектре появляются дискретные составляющие. Опираясь на распределениях статического давления, измерениях пульсации давления, визуализации течения шлирными методами, картине течения в плоскости x-t, а также на измерениях интенсивности и спектров шума, изучено структуру течения и описано механизм возникающих явлений.

Notation

AP amplitude in spectrum of pressure oscillation,
D duct diameter,
d nozzle diameter,
d_c central body diameter,
f frequency,
H vortex pitch,
$OSPL$ overall sound pressure level in [dB],
$\Delta OSPL$ $OSPL - OSPL_*$ [dB],
p pressure,
$\bar{p}_0$ $\dfrac{p_0}{p_{0*}}$,
$\bar{p}$ $\dfrac{p}{p_0}$,
Δp double amplitude of pressure oscillation,
$\Delta\bar{p}$ $\dfrac{\Delta p}{p_0}$,
SPL sound pressure level in [dB],
ΔSPL $SPL_f - OSPL$ [dB],
t time.

x coordinate along duct measured from nozzle,

$\bar{x}$ $\frac{x}{D}$,

φ ratio of nozzle area to duct area.

Suffixes

c central dead-air region,

f at definite frequency,

0 supply,

w outer dead-air region,

$*$ appearance of sonic outflow from nozzle.

1. Introduction

IT is well known that circular, sonic, choked jet of a gas in certain circumstances reveals some modes of oscillation (Fig. 1) and produces noise distinctive by discrete frequencies in sound pressure level spectrum. These discrete tones are often called "screech", The mechanism of their generation involves the coupling of flow and acoustic phenomena. The noise of choked jets has been investigated by POWELL [1], DAVIES and OLDFIELD [2], MERLE [3], WESTLEY and WOOLLEY [4] and others.

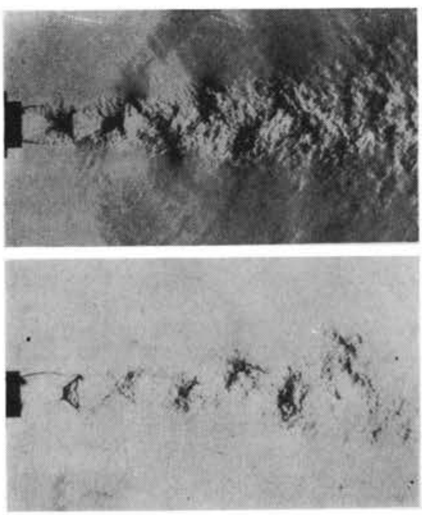


FIG. 1.

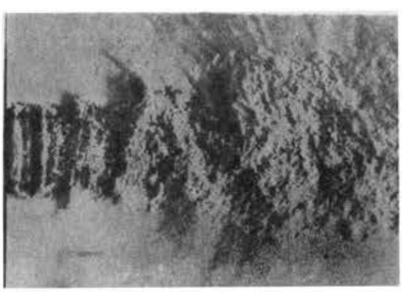


FIG. 2.

Annular free jet possesses properties very similar to the circular one at adequate supply pressure level [5]. Oscillating it desintegrates also rapidly (Fig. 2) and produces strong noise.

2. Experimental results

We shall describe some peculiar features of an annular jet expanding into concentric cylindrical duct (Fig. 3) and producing powerful noise [5]. The mechanism of the phenomenon is supposed to be also of an acoustic feedback type.

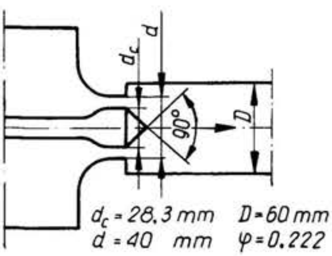


FIG. 3.

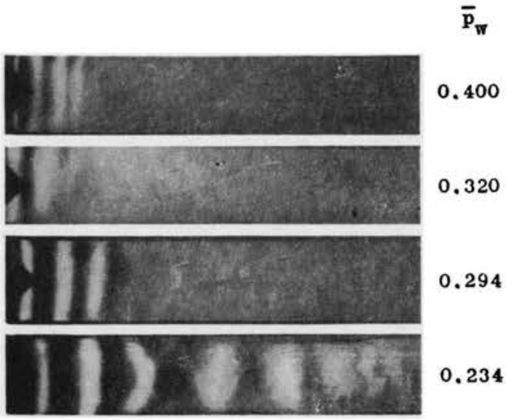


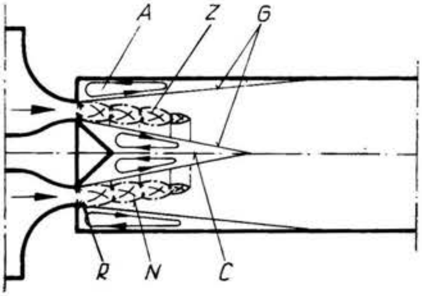
FIG. 4.

The photographs in Fig. 4 show the central portion of the stream visible through windows in height equal to half the diameter of the duct. At $\bar{p}_w = 0.320$ the flow reveals some oscillations. The cellular jet structure corresponding to the considered pressure range is sketched in Fig. 5.

It was observed that the $\bar{p}_c$ (Fig. 6) was lower when oscillation existed and higher (dashed line) when it was prevented by two spoilers (width 3 mm, height 2 mm), inserted at the nozzle outlet.

The curves of static pressure distribution along the duct (Fig. 7, $\bar{p}_w = 0.320$), corresponding to oscillation and without it (dashed line), are also different. From above results some conclusions might be drawn. Due to the oscillation the jet desintegrates more rapidly and its angle of divergence is greater. In consequence the flow reattachment at the wall of the duct occurs closer to the nozzle and the central dead-air region is diminished.

The increase of overall sound pressure level versus $\bar{p}_w$ exhibits maximum, corresponding to the oscillation, in the same range of non-dimensional pressure for the free annular jet as well as for the jet expanding into the duct (Fig. 8). In Fig. 9, very high $\Delta OSPL$ appearing simultaneously with the oscillation might be noticed. Prevention of the oscillation by application of spoilers reduced the noise significantly in wide range



A - outer dead-air region,
C - central dead-air region,
G - jet boundary,
N - supersonic flow boundary,
R - expansion wave,
Z - compression wave.

FIG. 5.

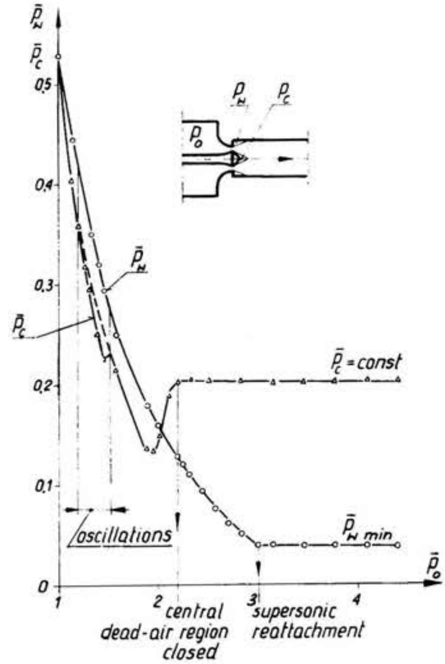
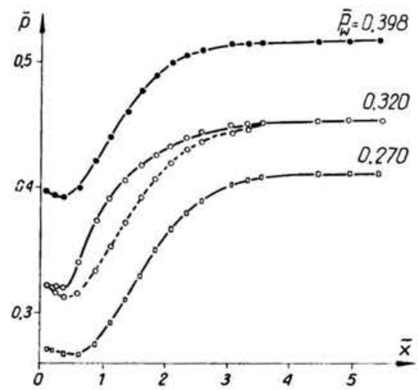


FIG. 6.



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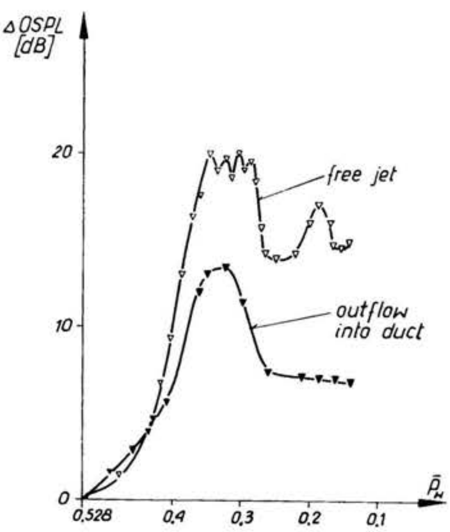


FIG. 8.

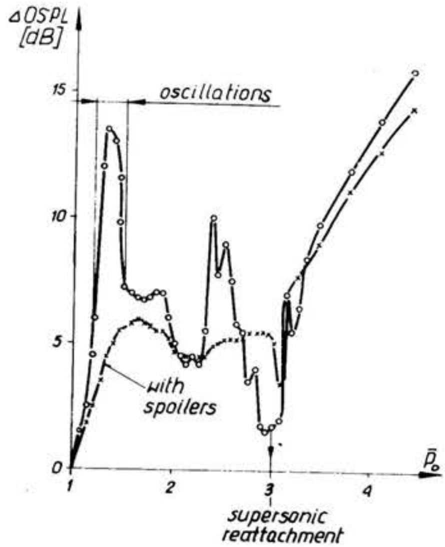


FIG. 9.

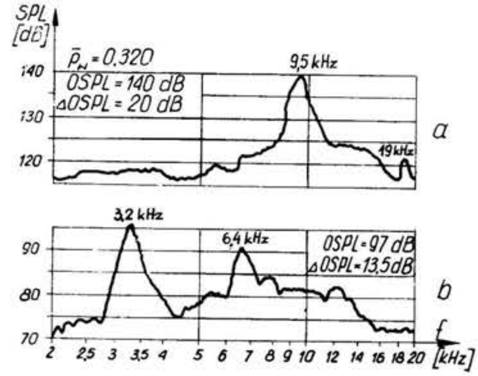


FIG. 10

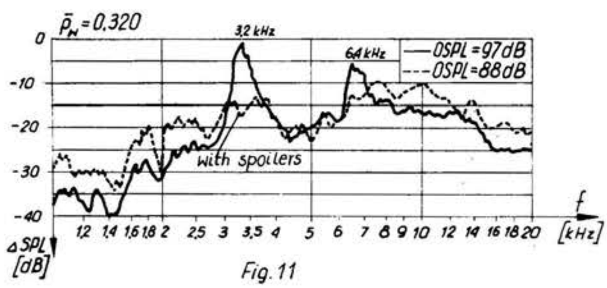


FIG. 11.

of $\bar{p}_0$, however increased the minimum value of it due to turbulence intensity growth. Comparison of *SPL* spectra (Fig. 10) shows that the discrete frequencies generated by the free annular jet (a) are about three times higher than those generatet by the jet expanding into the duct (b). Absence of the oscillation due to the spoilers is manifested by elimination of discrete frequencies from the *SPL* spectrum (Fig. 11, dashed line).

Pressure oscillations in the duct were recorded at several cross-sections at different points of the wall circumference. Some of the pressure traces corresponding to $\bar{x} = 0.1$ and $\bar{x} = 1.6$ are shown in Fig. 12. Pressure oscillations are in phase opposition (a, f) and in phase (b, g) at opposite points for both cross-sections. From comparison of traces obtained simultaneously at two cross-sections ($\bar{x} = 0.1$ and 1.6) we see that they are in phase opposition at one side of the duct (c) and in phase at two opposite sides (e). The analysis of phase shift for these and other traces shows that some pressure disturbances are moving helically in the duct with constant frequencies equal to the discrete frequencies of *SPL* spectrum.

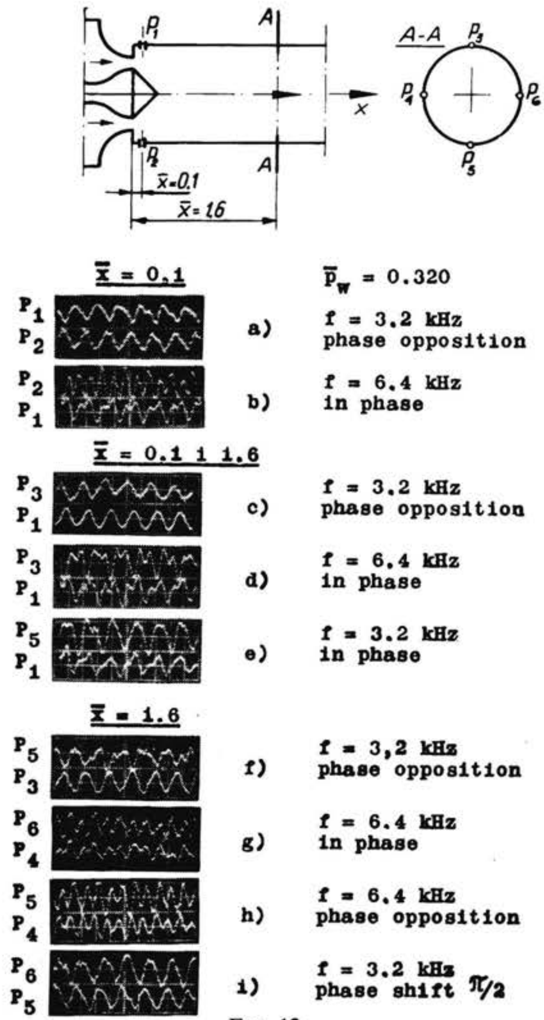


FIG. 12.

Spectra of pressure oscillations recorded at various locations along the duct are presented in Fig. 13. The same dominant frequencies appear, which we observed already on the pressure traces (Fig. 12). The amplitude of pressure oscillations is growing along the duct (Fig. 14) reaching its maximum in the region of jet reattachment ($\bar{x} = 1.6$), which was detected by oil film technique. The wavy distribution of amplitude further downstream might be caused by circulation of reattachment point inducing some modes of cross-oscillation. *OSPL* distribution exhibits one maximum at nozzle and other in the region of reattachment.

The streak-picture (Fig. 15) shows disturbances (v) appearing near the nozzle, with frequency equal to the first harmonic of discrete frequency of *SPL* spectrum and of pressure oscillations spectrum. These disturbances are moving downstream with the speed close to half of gas velocity at the supersonic boundary of the jet and they disappear in the reattachment region.

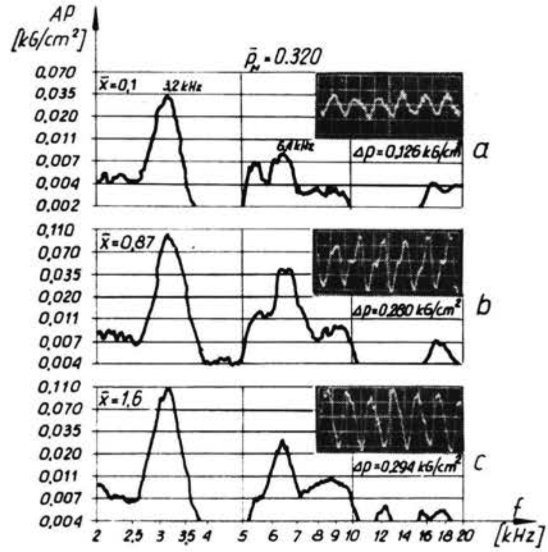


FIG. 13.

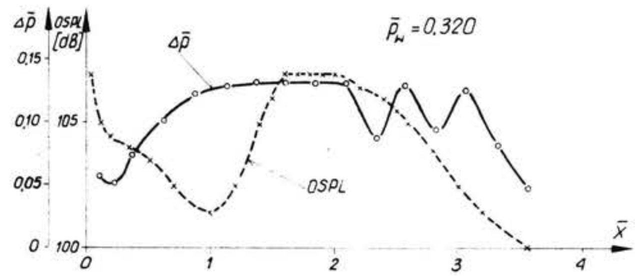
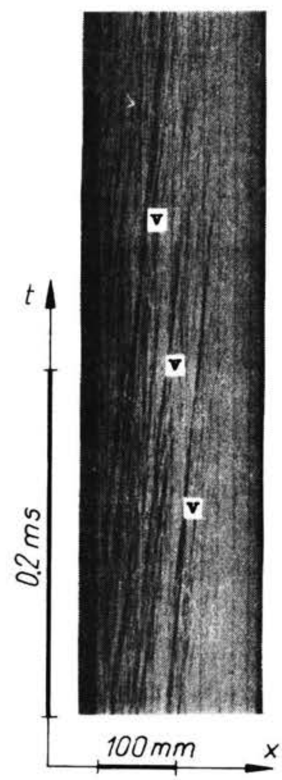


FIG. 14.



$\bar{p}_w$ = 0.320

FIG. 15.

3. Conclusions

Above observations indicate that pressure disturbances are due to the spiral vortex (Fig. 16), one end of which is circling around the nozzle and the other around the duct wall at reattachment cross-section. From analysis of pressure traces, streak-picture and from simple calculations results that one and a half pitch of one vortex or of two vortices exists in the duct. It is puzzling, however, that the presence of two vortices has been intermittent. The first harmonic of discrete frequency in *SPL* spectrum and pressure oscillations spectrum have appeared and disappeared irregularly. This is not revealed on the streak-picture, because two vortices move along the central slit simultaneously.

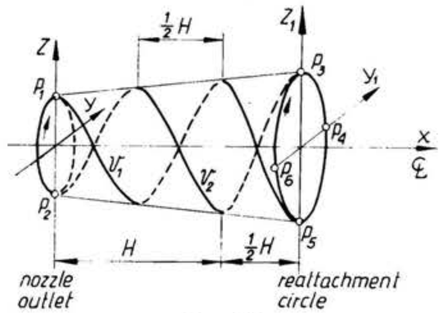


FIG. 16.

In conclusion of all our observations and from comparison with the results obtained by WAGNER [6] and NEUWERTH [7], who have investigated free jets impinging on flat obstacle, we suppose that in the discussed case the flow and accoustic phenomena are coupled in a similar manner. When free shear layer at the nozzle outlet is unstable and acoustic wave radiated from reattachment region is reaching the nozzle through dead-air region, the spiral vortex is generated. This vortex, after being convected downstream and strengthened, impinges on the wall and generates acoustic wave thus closing a feedback loop.

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