ARCHIVES OF ACOUSTICS
6, 2, 123-134 (1981)

ON THE INFLUENCE OF THE NOZZLE EXTERNAL CONFIGURATION ON THE RADIATED SCREECH AND THE DECAY OF SUPERSONIC JETS*

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The behaviour of screeching jets exhausting from an axisymmetric convergent-divergent nozzle was studied. The nozzle had a 2.9 mm throat diameter and a 1.95 theoretical exit Mach number. Compressed nitrogen was used to obtain nozzle stagnation pressures from 0.15 to 1.4 MPa (absolute), i.e. conditions of overexpanded, correctly expanded and underexpanded streams at the nozzle exit section. The jet exhausted into a free field room and tests were performed for several nozzle external configurations. Measurements were made in terms of noise level emitted by the jet and impact pressure downstream. It was found that in the weakly overexpanded and in the underexpanded regimes the nozzle external configuration influences markedly the screech intensity while it does not affect substantially its frequency. The latter generally decreases as the stagnation pressure increases; in particular in the weakly overexpanded regime two screeching frequencies are present for a given stagnation pressure. High intensity screech jets have down-stream impact pressures lower than low intensity ones and therefore higher decay rates. Even for correctly expanded jets, screech levels and impact pressures are configuration influenced. In the strongly overexpanded regime, several harmonically related spectral peaks are present whose frequencies increase for increasing stagnation pressure; they appear not to be substantially influenced by the nozzle configuration but correspond, rather, to pure shock noise.

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* Work sponsored by National Research Council of Italy (C.N.R.).

1. Introduction

It is well established that the noise emitted by jets strongly depends on the fluid dynamic field associated with them. LIGHTHILL [12] gave an analytical theory, describing the generation of aerodynamic noise in subsonic jets, which predicts that the overall sound power is proportional to the eighth power of the jet speed. This theory, however, is not applicable to the theoretical prediction of the noise emitted by choked jets having a shock cellular structure, which show a peculiar behaviour.

The complex interaction between the jet shock structure and the turbulent mixing flow, the oscillation of the shock itself, and the interaction of the radiated noise field with the fluid dynamic field and the ambient configuration (near the origin of the jet), make the whole problem rather cumbersome so that a satisfactory descriptive model is still far off. Much of the knowledge rests on experimental results from which some insight into the noise generation mechanisms has been gained. For jets having a shock structure these mechanisms may be roughly divided into three classes:

1) turbulence noise due to fluctuations of momentum flux;

2) shock noise associated with instability of the shock, arising when the convected turbulent eddies pass through it;

3) screech, a particular narrowband shock noise enhanced by a type of regenerative amplification.

The latter is of primary interest within the present context.

POWELL [17] first gave a model for the screech phenomenon which was later confirmed in more detail by DAVIES and OLDFIELD [5]. Briefly, the mechanism can be described in the following manner. Sound waves, arising when a flow disturbance convected downstream interacts with the shock cell pattern of the jet, propagate themselves upstream toward the nozzle exit section where they slightly affect the nozzle pressure ratio. This event results in a disturbance of the flow, growing up like a vortex, which is convected downstream along the jet boundaries. The vortex, in turn, excites the emission of sound waves. When the right conditions exist, the feedback loop is selfsustained by tuning itself at certain discrete frequencies: the screech tones.

The general interest in the problem is connected with three different areas:

1. noise "per se", since the screech tones, if they lie in the audible frequency range, may be by far the loudest component of the noise;

2. structural damage, since the hypothesis that the screech severely fatigues aircraft structures has been put forward [10, 18];

3. jet decay process, since the screech affects the spreading of the jet itself [1-4, 7].

Much work has been published [11, 13-15, 20] describing, phenomenologically, the screech and the characteristics of the jets from which it originates.

More or less empirical relationships have been given which predict the screech frequency for the tested conditions, although the screech intensity remains essentially unpredictable. All the papers on the problem are generally related to underexpanded jets issuing from two-dimensional plane and axisymmetric convergent nozzles (choked jets). With regard to the frequency of the screech tones, changes in the upstream stagnation pressure result in quite different behaviour for the two types of jets. Two-dimensional plane jets show a continuously decreasing screech frequency with increasing stagnation pressure, while axisymmetric jets, still retaining this general trend, also exhibit remarkable jumps in the screech frequency in certain stagnation pressure ranges. This discontinuous behaviour is closely related to sharp changes in the cell pattern [5].

Referring to the screech intensity and to the jet decay characteristics, several papers [5, 7-9, 17, 19] show the influence on the radiated noise and/or on the jet decay, of both sound absorbing and sound reflecting surfaces placed near the nozzle orifice. The very solid annular zone surrounding the exit section of the nozzle itself can modify both the noise and the decay of the jet [1-4, 16].

In fact the ambient configuration near the origin of the jet interacts with the sound waves propagating upstream and therefore a peculiar feedback system is set up. One may conclude that modifications of the ambient configuration can be used, in a sense, to distinguish pure shock noise from shock noise that can be tuned into by the feedback system and which turns out as screech. This is indeed implicitly done in the study of pure shock noise where screech is suppressed with sound absorbing layers or small projections on the nozzle lip [9]. It has to be pointed out that this practice is not correct if the turbulent noise component of a particular jet is to be studied. In fact, since the jet decay is highly influenced by the screech tones, a different decay can in turn influence the broadband noise. To authors' knowledge, at the present time little screech data has been published for jets issuing from convergent-divergent nozzles, i.e. jets which start supersonically. In the present context, these nozzles have mainly been considered as means to suppress screech noise [6, 21], in the sense that a correctly expanded jet, having a practically shockless structure, will lack any screech.

The aim of this work has been to investigate experimentally those screeching jets which emit supersonically (i.e. issuing from a convergent-divergent nozzle), to determine their behaviour above and below the theoretically correct nozzle pressure ratio. The main motivation is that a cellular shock pattern exists both for underexpanded streams (as for choked jets) and for overexpanded streams.

2. Experimental procedures

The measurements were performed in a free field room. The tested nozzle shown in Fig. 1, has a 2.9 mm throat diameter, a conical divergent with 1 : 20 taper ratio, and a 1.95 theoretical exit Mach number. Compressed pure nitrogen at nearly room temperature was sent to the nozzle through a pressure regulating valve and a settling chamber. The stagnation pressure was varied from 0.15 up to 1.4 MPa (absolute). Both the settling chamber, that was placed in the free field room, and its supporting structures were lined with sound absorbing acoustic foam in order to reduce the influence of reflected waves on the jet noise field. A 1.5 mm OD externally chamfered pitot tube was placed on the jet axis at 300 mm from the nozzle exit section. Schlieren visualizations, not reported herein, were performed at various pressure ranges.

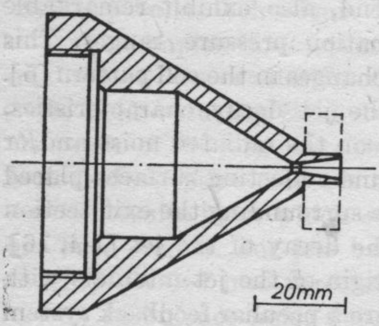

Fig. 1. Configurations of the tested nozzle; the broken line indicates the 26 mm OD brass flange

The noise was measured, at 150° to the downstream oriented jet axis [3] and at 1 m from the center of the nozzle exit section, with a B and K type 4133 ½″microphone and recorded on a Nagra IV-SJ tape recorder which had a frequency response ±1.0 dB from 25 Hz to 35 kHz and a − 3 dB point at 40 kHz The recorded noise was subsequently analysed with a B and K system consisting of a 2120 noise frequency analyser and a 2305 graphic level recorder. Frequency spectra were obtained, for both 3 % and 1 % constant percentage bands, swept over the range 6.3-50 kHz. Due to the tape recorder characteristics the pressure level spectra presented are slightly understimated in the range 35-40 kHz and greatly underestimated in the range 40-50 kHz. Peak frequency values in the range 35-50 kHz have been detected with a 1 % bandwidth. Since the noise analyser allowed frequency analysis up to 20 kHz, during the play mode the tape was slowed down by a 1:10 speed ratio in order to accomodate the recorder frequency band in the 3Hz-20 kHz analyser band available.

Most of the tests were performed with both of the external configurations represented in Fig. 1 where the broken line indicates a 26 mm OD brass flange. In the tests without the flange the thickness of the annular zone surrounding the nozzle exit section was about 0.8 mm. Some tests were also performed with two different (13 and 49 mm OD) brass flanges and with a 26 mm OD sound absorbing flange.

3. Results and discussion

The diagrams of Fig. 2 show the 3 % bandwidth sound pressure level spectra of the noise emitted by the jet for the two nozzle external configurations represented in Fig. 1, i.e. the nozzle without a flange, and the nozzle with the

26 mm OD brass flange. Each line corresponds to a particular value of the stagnation pressure, p_0, which varies from one corresponding to almost correct nozzle expansion (theoretically located at $p_0 = 0.73$ MPa), to values that involve an underexpanded stream at the nozzle exit section. On the basis of the diagrams of Fig. 2 and of other tests performed, the following conclusions can be drawn:

– Each spectrum shows a marked peak at a given frequency. The 1% bandwidth analysis has shown that these peaks are narrowband in nature. In accordance with previous results [17], especially at the high pressures and for the "with flange" tests, a second peak has been found at twice the frequency of the first one. The amplitude of the signal in the range 40-50 kHz, and in particular for the harmonic peaks, is underestimated since the tape recorder attenuated the signal (see previous section).

– The peak frequency seems substantially independent of the nozzle external configuration. This behaviour has been confirmed by the tests performed with different OD brass flanges, and with the sound absorbing flange.

– The difference between the peak pressure levels for the two configurations of Fig. 1 is irrelevant at the stagnation pressure $p_0 = 0.7$ MPa which

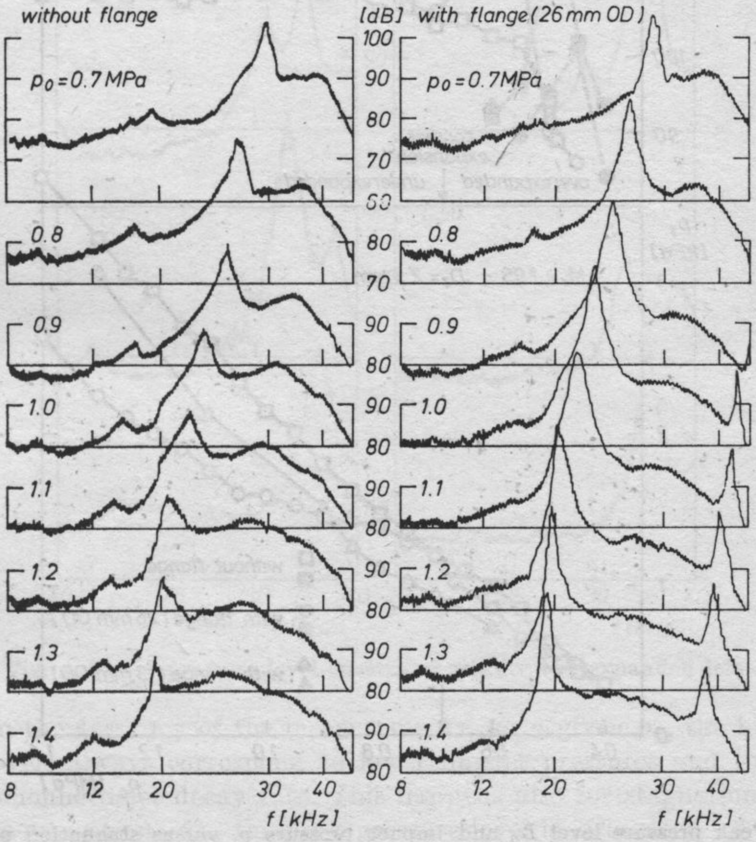

Fig. 2. Sound pressure level spectra of almost correctly expanded, and underexpanded jets

corresponds to almost correct nozzle expansion (a similar result has also been found at $p_0 = 0.75$ MPa), but it increases with increasing stagnation pressure. At $p_0 = 1.3$ MPa the peak pressure level of the noise emitted by the jet issuing from the nozzle with a flange is about 18 dB higher than that from the nozzle without a flange. Some tests performed with the other brass flanges have shown peak pressure levels which are generally intermediate between those related to the two different configurations of Fig. 1. A completely different behaviour has, however, been found in tests performed at $p_0 = 0.7$ MPa, with both the 13 mm and the 49 mm OD brass flanges, which showed peak pressure levels about 10 dB higher than those corresponding to the two configurations of Fig. 1. Tests

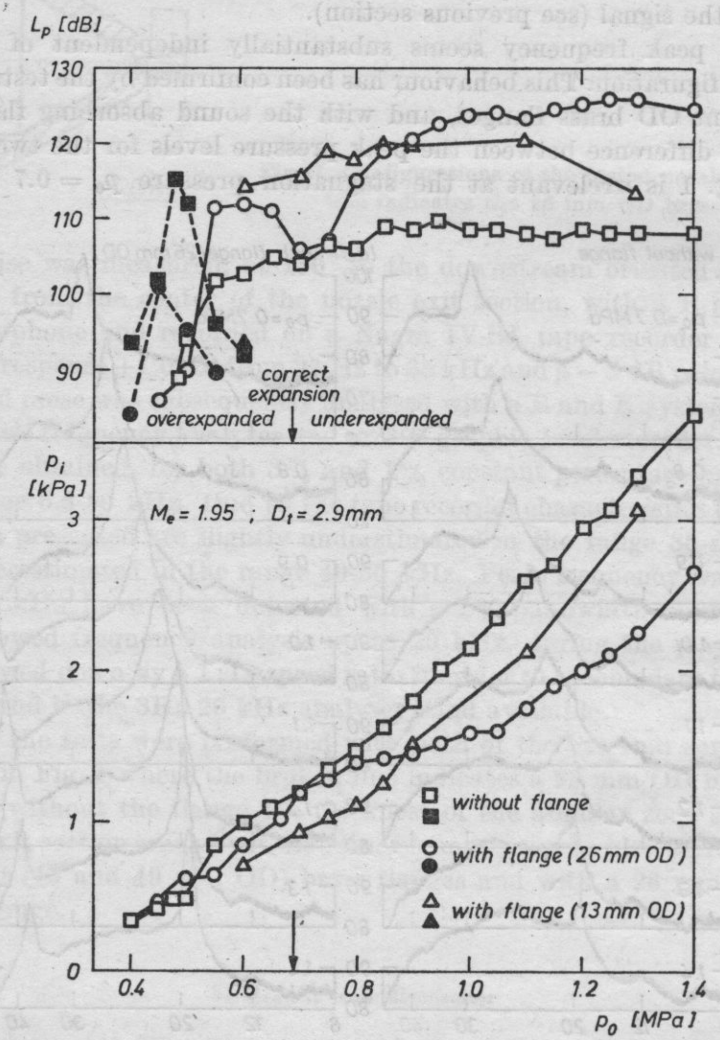

Fig. 3. Peak pressure level L_p and impact pressure p_i versus stagnation pressure p_0

performed with the sound absorbing flange have indicated peak pressure levels which are about 3 dB lower than those corresponding to tests without a flange.

– The peak frequency decreases with increasing stagnation pressure.

The peak pressure level values, L_p (for the nozzle external configurations: without a flange, with 26 mm and with 13 mm OD brass flanges) have been compared in Fig. 3 with the measured impact pressures p_i for a wider range of the stagnation pressure p_0.

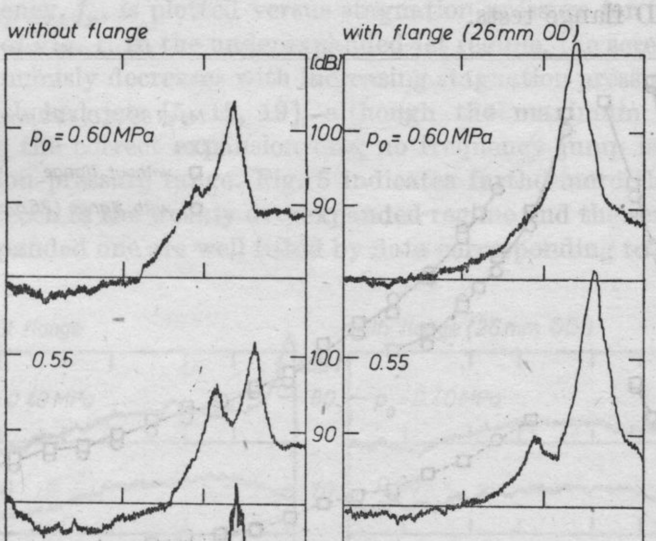

Fig. 4. Sound pressure level spectra of weakly overexpanded jets

Within the accuracy of the measurements, for a given p_0, the higher peak pressure levels always correspond to lower impact pressures and therefore to a more pronounced jet decay rate. This happens also for stagnation pressures close to the correct one, i.e. the peak pressure level is influenced by the nozzle configuration and so is the impact pressure. It has to be pointed out, however, that in this range the smaller flange (13 mm OD) shows high peak levels, while the larger one (26 mm OD) influences neither L_p nor p_i. These results are in accordance with the results previously reported by the present authors [2, 3]. Schlieren visualizations showed that the higher the peak pressure level of the jet, the lower was the number of its apparent cells; e.g. at $p_0 = 1.1$ MPa eleven cells were visible for runs without a flange, while only eight were seen during the 26 mm OD flange tests.

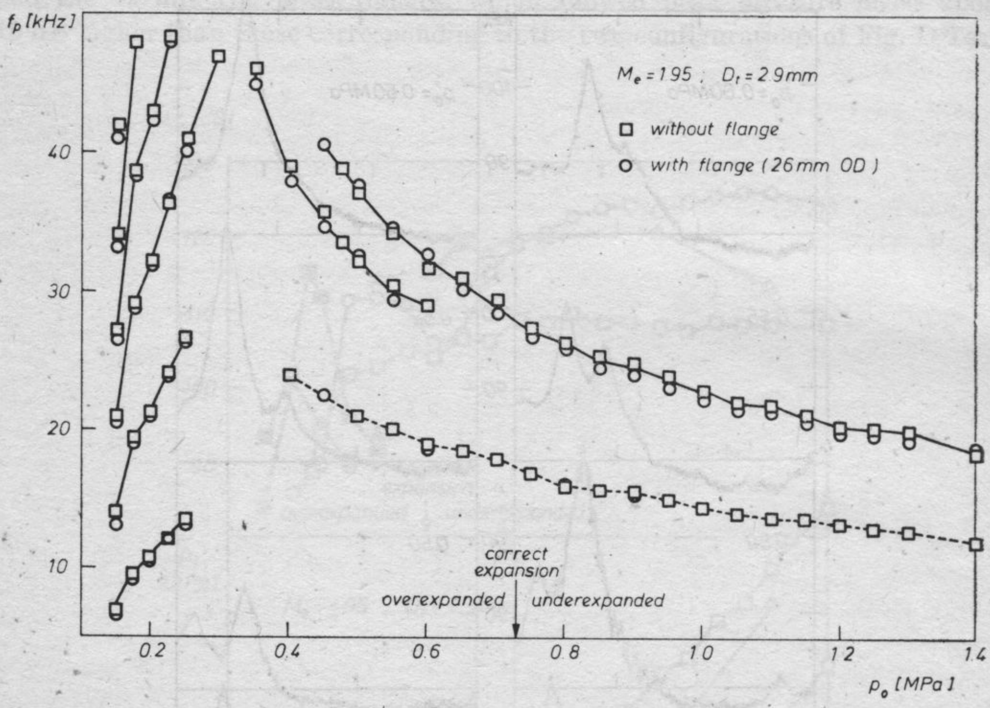

Fig. 5. Frequency of the sound pressure level peaks f_p versus the stagnation pressure p_0

In the low stagnation pressure range of the $L_p - p_0$ diagram, two symbols appear for each configuration; the open ones correspond to the tone already encountered in the high p_0 range, while the closed symbols correspond to a lower frequency tone which arises at low stagnation pressures. This is shown in Fig. 4 where the 3 % bandwidth sound spectra show that, as the stagnation pressure decreases, there is an onset of a secondary peak that progressively replaces the previous one which eventually vanishes. Both peaks occur at frequencies that decrease with increasing stagnation pressure. The behaviour described seems to be "delayed" in the "with flange" tests.

For very low stagnation pressures (see Fig. 3) this secondary peak also tends to decrease its intensity, and its effect on the impact pressure. The sound spectra of Fig. 4 suggest the simultaneous presence of two relatively high intensity screeching tones for a significant range of stagnation pressures. However, it has to be pointed out that, since the analyser integrates signals in time, the two peaks found could possibly be due to continuous jumping of the feedback loop between two almost stable configurations to which the two different screech tones correspond. Also in this pressure range, Schlieren visualizations showed essentially the same behaviour as was described for the underexpanded jets.

The overlapping range of the two screech tones is also evident from Fig. 5 where the peak frequency, f_p, is plotted versus stagnation pressure for the two nozzle configurations of Fig. 1. In the underexpanded jet regime, the screech frequency (full line) continuously decreases with increasing stagnation pressure. Unlike the behaviour for choked jets [5, 15, 19], although the maximum pressure ratio is almost twice the correct expansion one, no frequency jump is found in the tested stagnation pressure range. Fig. 5 indicates furthermore that the higher tones of the screech in the weakly overexpanded regime and the screeching tones of the underexpanded one are well fitted by data corresponding to nearly correct expansion.

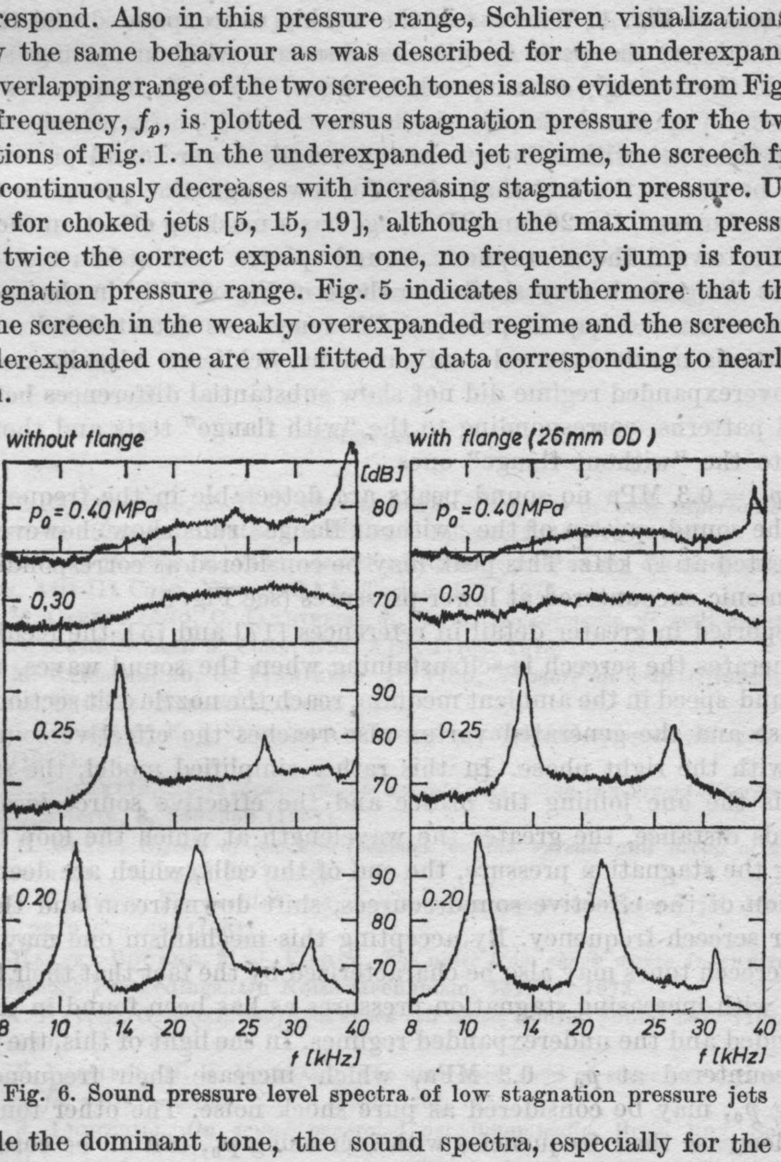

Fig. 6. Sound pressure level spectra of low stagnation pressure jets

Beside the dominant tone, the sound spectra, especially for the "without flange" tests, show a secondary peak (dashed line in Fig. 5), at a lower frequency, which also decreases in amplitude with increasing p_0 without showing any shift of frequency. This peak, of much lower pressure level, is evident in some of the spectra of Figs. 2 and 4. It behaves like a screeching tone and starts to appear in the weakly overexpanded jet region at $p_0 = 0.4$ MPa (Fig. 6).

The data in Fig. 5 also shows the frequencies of the sound pressure level peaks which are present in the strongly overexpanded jet regime. These peaks, which are harmonically related, are evident, at low stagnation pressure values, in the 3 % bandwidth sound spectra of Fig. 6 obtained for the two different nozzle configurations of Fig. 1. Whereas in the weakly overexpanded and the underexpanded regimes, the peak frequencies decrease with increasing stagnation pressure, in the strongly overexpanded regime, the peak frequencies increase. The two sets of spectra look very similar except at high frequencies where the spectra of the tests with a flange show generally lower sound pressure levels. This may be due to the fact that, since for low stagnation pressures the shock cell pattern shortens, the 26 mm OD flange has a masking effect on the jet noise propagation toward the microphone. Sound spectra obtained in tests with the other brass flange look very similar to those of Fig. 6. Within the accuracy of the measurements no impact pressure difference was detected below 0.3 MPa for the various nozzle external configurations. Schlieren visualizations in the strongly overexpanded regime did not show substantial differences between the shock cell patterns corresponding to the "with flange" tests and those corresponding to the "without flange" ones.

For $p_0 = 0.3$ MPa no sound peaks are detectable in the frequency range shown. The sound spectra of the "without flange" runs show, however, a peak that is located at 47 kHz. This peak may be considered as corresponding to the third harmonic encountered at lower pressures (see Fig. 5).

As reported in greater detail in references [17] and [5], the feedback loop which generates the screech is selfsustaining when the sound waves, travelling at the sound speed in the ambient medium, reach the nozzle exit section with the right phase and the generated vortex also reaches the effective sound source location with the right phase. In this rather simplified model, the significant distance is the one joining the orifice and the effective source location: the greater this distance, the greater the wavelength at which the loop tunes. By increasing the stagnation pressure, the end of the cells, which are deemed to be the location of the effective sound sources, shift downstream and this results in a lower screech frequency. By accepting this mechanism one may conclude that the screech tones may also be characterized by the fact that their frequency decreases with increasing stagnation pressures as has been found in the weakly overexpanded and the underexpanded regimes. In the light of this, the dominant tones encountered at $p_0 < 0.3$ MPa, which increase their frequencies with increasing p_0, may be considered as pure shock noise. The other tones which, instead, decrease their frequencies with increasing p_0, can all be considered as screech tones and are therefore configuration influenced.

The present results present a phenomenology which is wider than the one usually encountered in experiments with choked jets. The cellular shock pattern, still present in the overexpanded regime and in the correctly expanded one (especially for conical divergent nozzles, as shown by Schlieren visualizations), is able to generate screeching tones which, if correctly tuned by the feedback mechanism (depending on the nozzle external configuration), again influence the emitted noise and the jet decay rate. This event is of particular importance for correctly expanded jets. In fact, it has been suggested [6] that, in order to suppress the screech noise of a jet operating at a high pressure ratio, there is a definite advantage in using a convergent-divergent nozzle designed for that pressure ratio instead of a simple convergent one. The present results show, however, that while this may be true for a specific configuration (cf. tests with the 26 mm OD brass flange), it is not in general true for different configurations as is indicated by the data at $p_0 = 0.7$ MPa for both the 13 mm and 49 mm OD brass flanges.

In any case, since convergent-divergent nozzles, especially in propulsion, are seldom operated at a fixed pressure ratio, the acoustic behaviour of the jet issuing from them is of great importance in practical applications.

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Received on December 29, 1979; revised version on October 31, 1980