ON SCREECHING JETS EXHAUSTING FROM AN AXISYMMETRIC SUPERSONIC NOZZLE +

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Abstract

The behaviour of screeching jets exhausting from an axisymmetric convergent-divergent nozzle was experimentally studied for several nozzle external configurations. The jet exhausted into a free field room and tests were performed by varying the external diameter of a flange flush mounted with the exit section of the nozzle. The latter had a 2.9mm throat diameter, a 1.95 theoretical exit Mach number and was fed with pure nitrogen at various stagnation pressures to reach at its exit section conditions of overexpanded,correctly expanded and underexpanded streams. Measurements were made in terms of noise level emitted by the jet and impact pressure downstream. In the strongly overexpanded regime,frequency spectra showed several harmonically related sound peaks which frequencies increased for increasing stagnation pressure;these spectra and the corresponding impact pressures were not substantially influenced by nozzle external configuration.Therefore these sound peaks cannot be considered as screech tones in the usual sense. In the weakly overexpanded and in the underexpanded regimes sound peaks behaving as screeches were detected;in fact the nozzle external configuration influenced markedly the screech intensity while it did not affect its frequency.The latter generally decreased as the stagnation pressure increased. In particular in the weakly overexpanded regime two different screech frequencies were found for a given stagnation pressure;they were not simultaneously present indicating an instability phenomenon in the jet structure. High intensity screech jets had always downstream impact pressure lower than low intensity ones and therefore higher decay rates accompanied by an increased low frequency broad band noise. Even for correctly expanded jets,screech levels and impact pressures were configuration influenced while frequency was not.

1. Introduction

A satisfactory descriptive model of the noise emitted by supersonic jets,i.e. jets having a shock cellular structure,is still to be developed.
The complex interaction between the jet shock structure and the turbulent mixing flow,the oscillation of the shocks themselves,and the interaction of the radiated noise field with the fluid dynamic field and the ambient configuration (nearby the origin of the jet) make theoretical predictions rather difficult so that much of the knowledge rests on experimental results. For jets having a cellular shock structure the noise components may be roughly divided in three classes: 1) turbulence noise,due to the fluctuations of momentum flux; 2)shock noise associated with unsteadiness of shocks arising when the convected turbulent eddies pass through them; 3) screech, a particular narrowband shock noise enhanced by a sort of regenerative amplification. The latter is of primary interest within the present context. Powell [1] first gave the model of the screech phenomenon which was later confirmed in more detail by Davies and Oldfield [2]. 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 towards the nozzle exit section where slightly affect the nozzle pressure ratio. This 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 again the emission of sound waves. When the right conditions exists,the feedback loop is selfsustained by tuning itself at certain discrete frequencies: the screech tones.
The general interest in the matter is connected to three different areas: i)noise "per sé", as those tones, if laying in the audible frequency range, may be by far the loudest component of the noise; ii) structural damage, as the hypothesis that the screech severely fatigues aircraft structures has been put forward [3,4] ; iii) jet decay process,as the screech affects the spreading of the jet itself [5,6,7] . Much work has been published [8,12] describing phenomenologically the screech and the characteristics of the underexpanded (choked)jets it originates from.More or less empirical relationships have been given which correlate the screech frequency with some test parameters,while the screech intensity remains essentially unpredicted.
As regards this matter, jets issuing from convergent-divergent nozzles, i.e. jets which originate supersonic, have only been considered as means to suppress screech noise [13] in the sense that a correctly expanded jet,having a practically shockless structure,will lack the screech. The aim of this work

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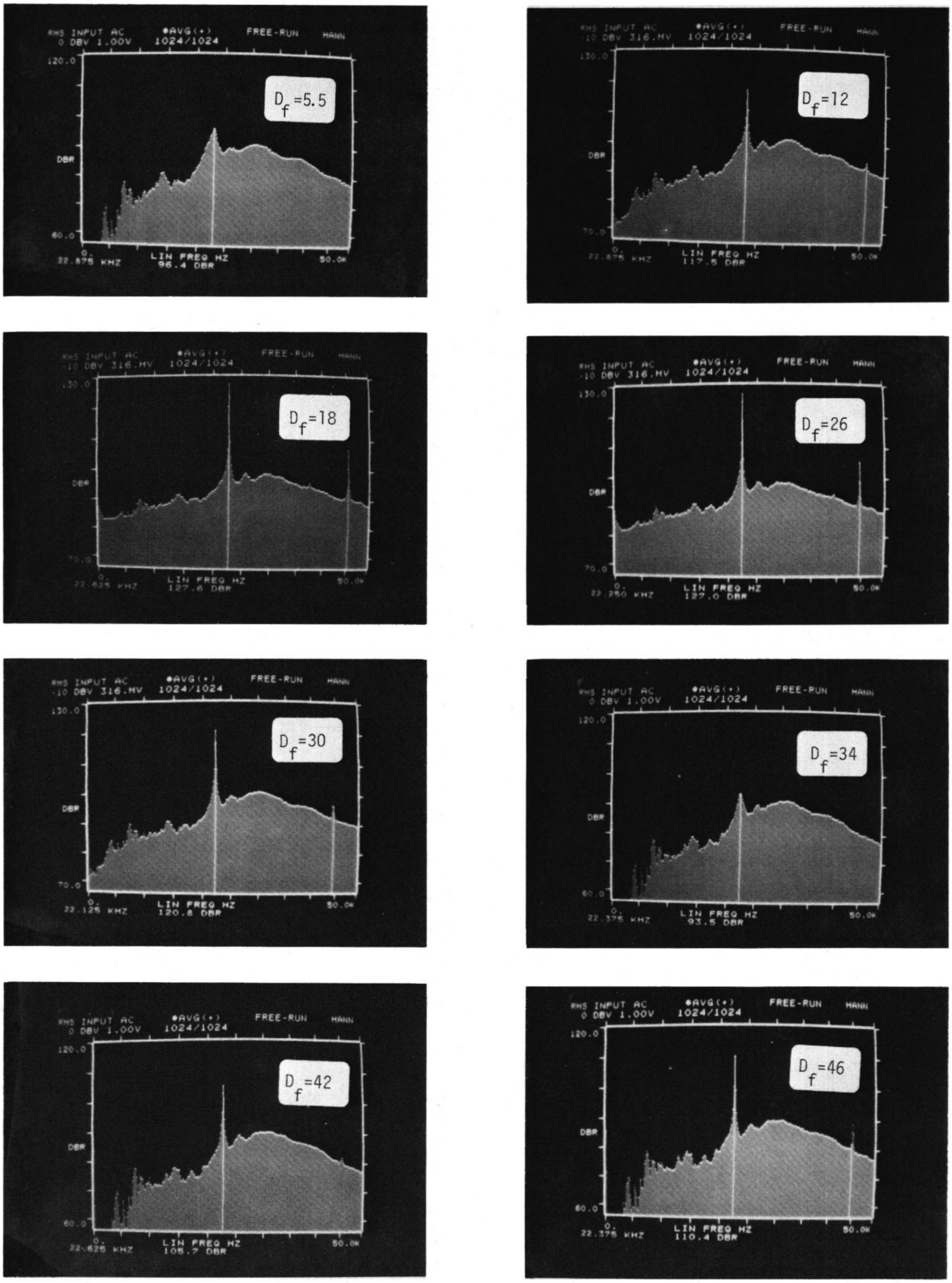

FIGURE 1. - Sound pressure level spectra at p_o = 1.1 MPa for different flange diameters D_f (mm).

has been to experimentally investigate screeching jets, which originate supersonic, above, at, and below the correct nozzle pressure ratio.

2. Experimental procedure

The measurements were performed in a free field room. The tested nozzle had a 2.9mm throat diameter a conical divergent with a 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 the reflected waves on the 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. The noise was measured, at 150° to the downstream oriented jet axis[7] and at 1 m from the center of the nozzle exit section, with a Bruel & Kjaer type 4133 ½" microphone and analysed with a Gen Rad 2512 Spectrum Analyzer, in the frequency range 0 - 50 kHz, which a constant equivalent bandwidth of 125 Hz corresponds to. The external configuration of the nozzle was changed by varying in the range 12 - 46 mm the external diameter of a flange flush mounted with the exit section of the nozzle; in the tests without flange the thickness of the annular zone surrounding the nozzle exit section was about 0.8 mm.

3. Results and discussion

Sound pressure level spectra (in the range 0-50 kHz) of the noise emitted by the jets for different flange diameters D_f are shown in Fig. 1 .All pictures are relative to the stagnation pressure p_0 =1.1 MPa (absolute) which corresponds to an underexpanded stream at the nozzle exit section. These pictures suggest the following considerations:

- Each spectrum shows a peak at a given frequency of about 22.5 kHz .The spectra which have a marked peak show also a second peak at twice the frequency of the first one.
- The peak frequency is almost independent of the nozzle external configuration ranging from 22,125 to 22,875 kHz. The peak pressure level instead depends strongly on D_f, ranging from 93.5 dB (D_f= 34 mm) to 127,6 dB (D_f= 18 mm).
- Except the presence of the screech peak, the high part of the spectrum is substantially independent of the flange external diameter D_f .
- As regards the low frequency part of the spectrum, there are three different behaviours: spectra for D_f=5.5-34-42-46 mm show relatively low sound pressure levels in the abovementioned frequency range; spectra for D_f=12-30 mm exhibit an increase of L_p in the same frequency range ;a further increase is present for D_f=18-26mm.

The spectra of the other underexpandedjets behave quite similarly, therefore it is possible to conclude that the ambient configuration nearby the origin of the jet does interact with the sound waves which propagate themselves upstream setting up a peculiar feedback system. Changes in the ambient configuration can be used ,in a sense, to detect pure shock noise from shock noise that can be tuned on by the feedback, which turns out as screech. This is indeed implicitely done in the study of pure shock and broadband noise where screech is suppressed with sound absorbing layers or small projections on the nozzle lip[14] . It has to be pointed out that this practice is incorrect also if the turbulent noise component of a particular jet is to be studied. Infact, as shown in Fig.1, the broadband low frequency noise is highly influenced by the screech tones, it increases for increasing peak pressure level.
The peak pressure level (L_p) have been compared in Figg. 2 and 3 with the pitot measured impact pressure (p_i) for two different stagnation pressures: p_o= 1.1 MPa and p_o= 0.7 MPa respectively; the latter corresponds about to the correct expansion within the nozzle. Higher peak pressure levels always involve lower impact pressures and therefore a more

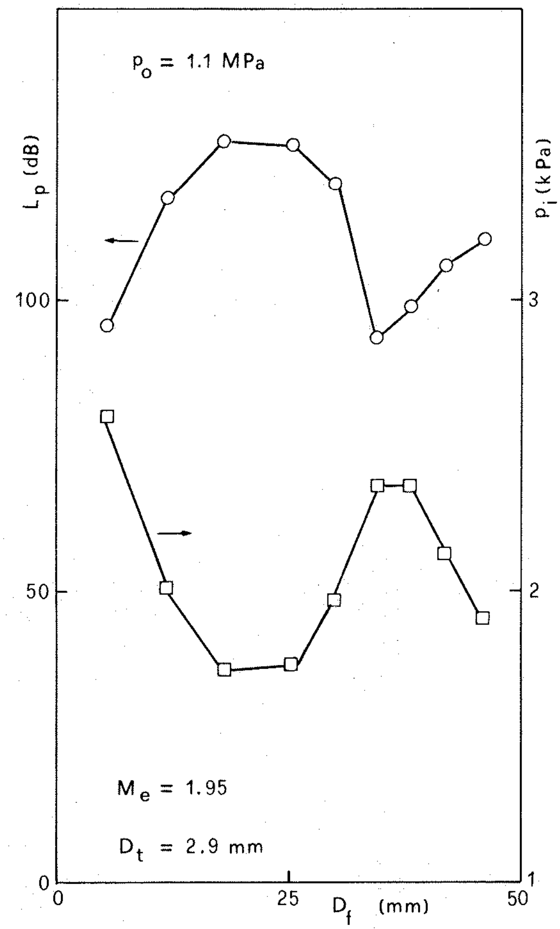

FIGURE 2. - Peak sound pressure level L_p and Pitot impact pressure p_i versus D_f at p_o= 1.1 MPa . (underexpanded jets)

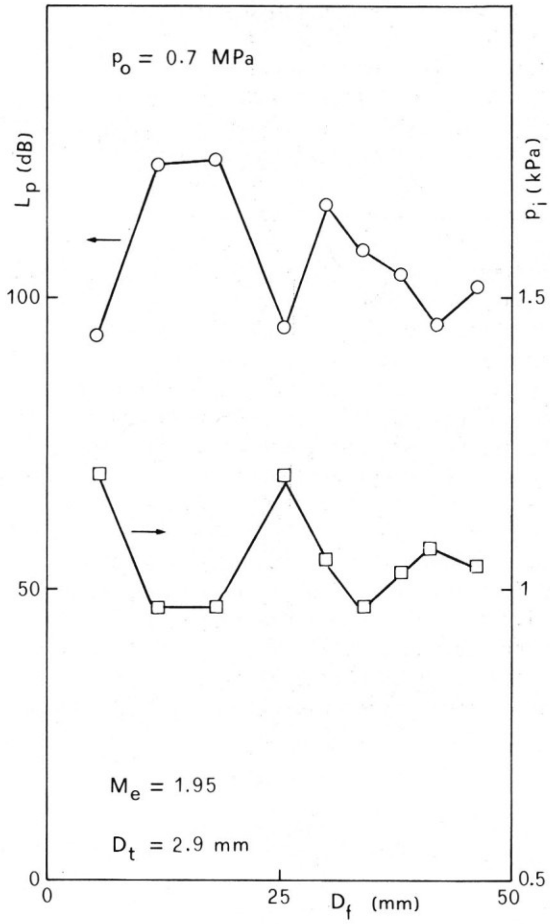

FIGURE 3. - Peak sound pressure level L_p and Pitot impact pressure p_i versus D_f, at p_o = 0.7 MPa (nearly correctly expanded jets)

pronounced jet decay rate, i.e. the peak pressure level is influenced by nozzle external configuration and so does the impact pressure. The value of D_f at which p_i is at a minimum (and correspondingly L_p is at a maximum) is lower the lower the stagnation pressure. Similar results have been obtained both for intermediate and higher stagnation pressures. This trend is in accordance with results previously reported by the present authors [6,7].

A typical spectrum in the weakly overexpanded regime (0.3 MPa $< p_o <$ 0.65 MPa) is shown in Fig. 4(a) where the onset of a second peak, which behaves also as a screech (i.e. is configuration influenced), is detected. This suggested the contemporaneous presence of two relatively high intensity screeching tones due to a continuous jumping of the feedback loop between two almost stable configurations which two different screech tones correspond to, not resolved because of the averaging process. The phenomenon was detected by listening to a tape recording of the noise sped down in the ratio 10:1. It is also clearly displayed in Figg.4(b) and 4(c) obtained with an averaging more appropriate to the situation. This unstable behaviour seems peculiar of the weakly overexpanded regime and depends strongly on the flange diameter D_f .

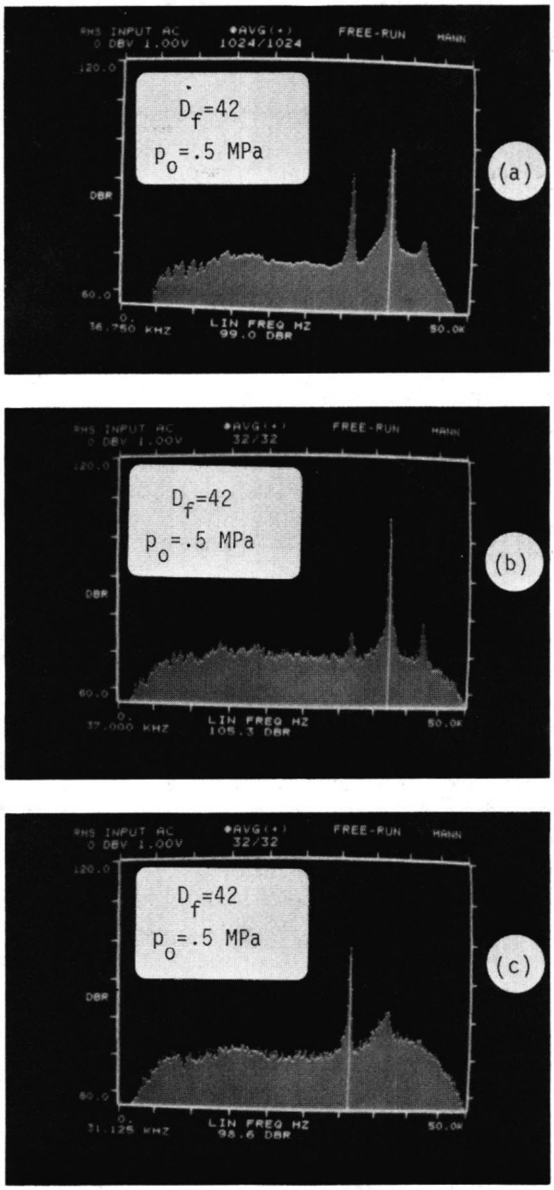

FIGURE 4. - Sound pressure level spectra at p_o = 0.5 MPa, for D_f=42mm; (a) long averaging time, (b) and (c) short averaging time

The overlapping of the two screech tones is also evident from Fig. 5 where the peak frequency, f_p, is plotted versus stagnation pressure for the without flange tests in that with flange tests do not show remarkable differences. In the underexpanded jet regime, the screech frequency continuously decreases for increasing stagnation pressure ; this behaviour has been found up to p_o=1.4 MPa which is the maximum tested stagnation pressure. Unlike for choked jets [2,9,10] , 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

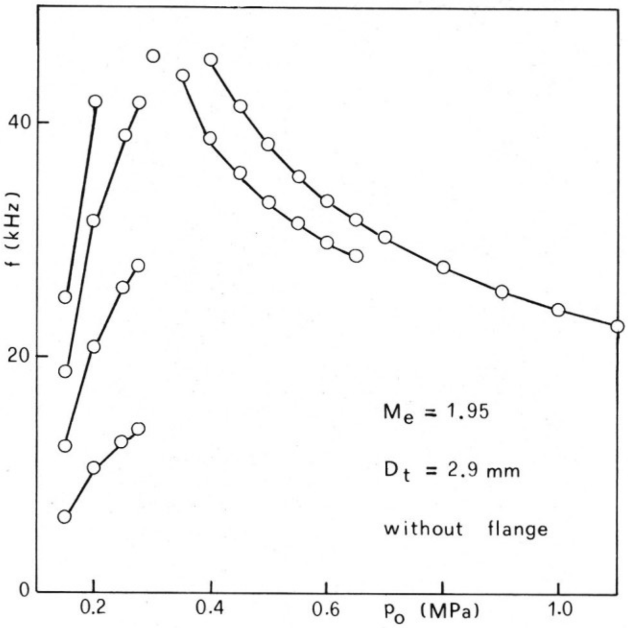

FIGURE 5. - Screech tones frequencies versus p_o for without flange tests (D_f= 5.5mm).

the underexpanded one are well fitted by data corresponding to nearly correct expansion. The data of Fig. 5 show also the frequency 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 sound spectra of Fig. 6 obtained for two different nozzle external configurations. While ,in the weakly overexpanded and in the underexpanded regimes,peak frequencies decrease for increasing stagnation pressures,in the strongly overexpanded regime peak frequencies increase.The two spectra of Fig. 6 look very similar except for the high frequencies where the spectra for D_f = 26mm show lower peak pressure levels.This may be due to the fact that,since for low stagnation pressures the shock cell pattern shortens, the flange has a masking effect on the propagation of jet noise toward the microphone. Sound spectra obtained in tests with the other flanges look very similar to those of Fig. 6 and within the accuracy of the measurements no impact pressure difference was detected in tests below 0.3 MPa for the various nozzle external configurations.

As reported in greater detail in references 1 and 2 the feedback loop which generates the screech is selfsustained when the sound waves, traveling at the sound speed in the ambient medium,reach the nozzle exit section with the right phase. In this rather simplified frame,the significant distance is the one joining the orifice and the effective sourcelocation:the greater this distance,the greater the wavelenght the loop tunes at. By increasing the stagnation pressure,the end of the cells,which are deemed to be the location of the effective sound

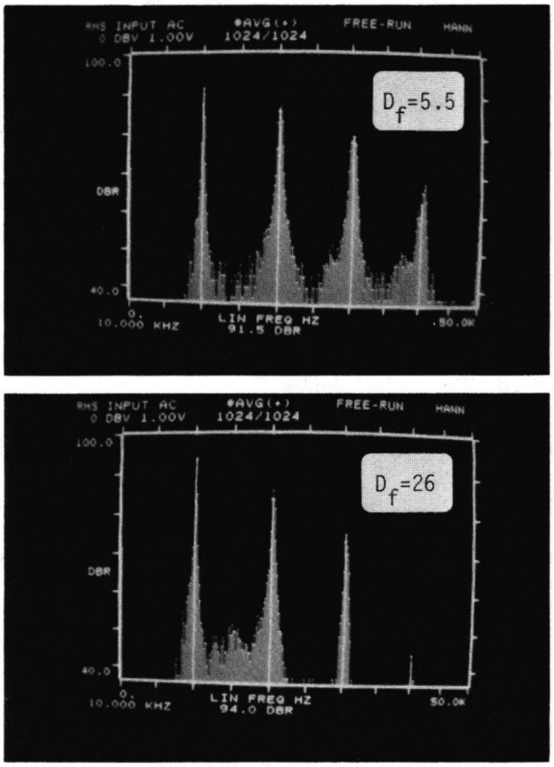

FIGURE 6. -Sound pressure level spectra at p =0.2 MPa

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 for increasing stagnation pressures their frequency decreases as it has been found in the weakly overexpanded and in the underexpanded regimes. The dominant tones encountered at $p_o < 0.3$ MPa increase their frequencies for increasing p_o, therefore they should be considered as pure shock noise. The other tones,instead,which decrease their frequencies for increasing p_o,may all be considered as screech tones and therefore are configuration influenced.

The present results bring up a phenomenology which is much different from the one usually encountered in previous experiments with choked jets. The cellular shock pattern, still present in correctly expanded (expecially for conical divergent nozzles) and overexpanded regimes,is able to generate screeching tones which,if tuned correctly by the feedback mechanism (depending on nozzle external configuration),again influnce the emitted noise and the jet decay rate. This event is of particular importance for correctly expanded jets.In fact, it has been suggested [13] that, in order to suppress screech noise of a jet operating at an 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 this may be true for a given configuration,while it is not true for different configurations as indicated by the data of Fig. 3 .

Furthermore the instability phenomenon found in the weakly overexpanded regime may give further hints about the screech generation mechanism . Finally it has to be pointed out that since the jet decay is highly influenced by the screech tones, a different decay can in turn influence the broadband noise; therefore even when studying the broadband noise the screech tones must be considered.

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