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Recent Observations Including Temperature Dependence of Axisymmetric Jet Screech

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Nomenclature

c	= sound speed in ambient air
c_{sl}	= sound speed in shear layer
d	= jet exit diameter
f	= screech frequency
f_r	= reduced screech frequency, defined in Eq. (4)
$K_1, ..., K_5$	= constants in the empirical representations
PR	= pressure ratio (total pressure/ambient pressure)
PR*	= pressure ratio at the onset of choking
R	= gas constant for air
T_{amb}	= temperature of ambient air
T_e	= jet exit static temperature
T_0	= jet total temperature
T_r	= reference total temperature
γ	= ratio of specific heats
$(\,)_T$	= quantity evaluated at temperature, T

Introduction

UNPUBLISHED investigations at ARL have indicated that jet screech phenomena can be used to increase the rate of entrainment by a confined jet. This was observed in a thrust augmenting ejector, where the screech of the primary jet drove an acoustic resonance within the mixing duct. In many ejector applications, the primary jet will be fed by hot engine exhaust gas. Therefore, it is desirable to quantify the dependence of jet screech of jet temperature.

Screech tones are emitted by sonic or supersonic jets operating at off-design pressure ratios. The acoustic frequency spectrum contains spikes at the screech frequency and its harmonics. Powell[1,2] has suggested a mechanism capable of explaining the occurrence of dominant frequencies. Briefly stated, he postulated the existence of stationary sound sources embedded in the cellular-flow structure which results from the off-design operation. The radiated sound waves travel upstream to the jet exit, destabilize the shear layer, and give rise to flow disturbances which are convected downstream. Each pass through a shock wave of the flow structure amplifies the disturbances. Ultimately, the disturbances attain sufficient strength to release a significant acoustic energy on traversing a shock wave. Since the waves are regularly spaced, only one fundamental signal frequency is amplified.

Powell investigated the screech emitted by an ambient temperature jet and established the dependence of the screech frequency on jet pressure ratio and characteristic dimension

$$f = K_1(c/d) \,/\, (PR - \text{PR}^*)^{1/2} \tag{1}$$

where: f = screech frequency, c = ambient speed of sound, d = jet exit diameter, PR = jet pressure ratio (total pressure/ambient pressure), PR* = jet pressure ratio at onset of choking, K_1 = empirical constant equal to ⅓ for axisymmetric jets. This expression provided an empirical fit to experimental data which contained a discontinuity in frequency. Powell applied two criteria in explaining the discontinuity. Based on considerations of the phase relationships between the sound waves and the flow disturbances, it was argued that the reinforcement necessary for a stabilized signal could be achieved only in a descrete number of flow conditions. This criterion was strongly linked to the distance downstream from the exit to the embedded sources. The second criterion demanded that the cycle amplification must equal or exceed unity. That is, the disturbance growth must compensate for losses in signal generation and transmission. The apparent discontinuities in dependence of frequency on pressure ratio were attributed to conditions failing to meet these criteria.

This Note presents an experimental investigation of the dependence of screech frequency on the total temperature of an axisymmetric, sonic airjet. In addition, some observations on the apparent frequency discontinuities are presented.

Experimental Apparatus

The experimental system consisted of an axisymmetric freejet, a variable temperature air supply, and a system to measure the sound power spectrum. The freejet had an exit diameter of 0.270 in. (1.06 cm). Air was supplied at either of three nominal temperatures: 60°F, 600°F, 1000°F (15°C, 315°C, 540°C, respectively), over a regulated pressure range exceeding six atmospheres. Pressure settings were held at specified levels to within ± ½%, temperature settings to within = 3%. A ½ in. diam Bruel and Kjaer condenser microphone was aligned at an angle of 30° upstream from the exit. The amplified signal was decomposed using a Tektronix 1L5 spectrum analyzer. Use of the manual frequency scan mode and a counter precisely identified the screech frequency for each operating condition.

Results

Figure 1 illustrates the experimentally determined variation of frequency with pressure ratio. Its form is in general agreement with Powell's expression, also shown on the figure. The deviation becomes substantial, however, for large pressure ratios. This is not surprising since Powell reported for a pressure range: PR < ~3.5. A better correlation is achieved by using an expression suggested by Merle[3]:

$$f = K_2(c/d) + K_3(c/d) \,/\, (\text{PR} - \text{PR}^*)^{1/2} \tag{2}$$

where K_2 and K_3 are constants. This expression is also plotted in Fig. 1 with values: $K_2 = 7.7 \times 10^{-2}$, $K_3 = 0.38$. Of course, neither relation predicts the discontinuity in experimental data. A closer look at the frequency spectra for pressure ratios in the neighborhood of the step revealed an interesting behavior. The apparent sudden shift of frequency was actually a simultaneous decrease in the screech spike at one frequency and increase at another. That is, as shown in the insert of Fig. 1, for increasing pressure ratio a discernable spike diminished until it was no longer distinct at PR ≈ 3.8. Concurrently, beginning at PR ≈ 3.4, a spike of higher frequency appeared. The apparent discontinuity indicated in Fig. 1 denotes the pressure ratio at which the two spikes had equal

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strength. Without a precise knowledge of the mechanism responsible for screech formation, it is not possible to explain this frequency shift and overlap fully. It is recognized that the sound sources exist several cells downstream of the jet exit. If it is accepted that the sound sources exist at the shockwaves separating the cells, then, for a certain range of pressure ratio, the characteristic length necessary for a strong screech production may not coincide with the shock wave locations. The waves immediately upstream and downstream, existing near the correct characteristic length, may be instrumental in simultaneously achieving weaker, stabilized signals. Criteria similar to those presented by Powell could determine which of these continues to exist for changes in pressure ratio.

The dependence of screech frequency on temperature is shown in Fig. 2 for three values of jet total temperature, T_0. At any pressure ratio, the screech frequency increases with temperature. The behavior of the frequency discontinuities is not consistent, however. At the lowest temperature ($T_0 = 65°$ F) the discontinuity is a shift in frequency, at the middle temperature (615^{0}F) two dominant frequencies appear near pressure ratios, PR $= 2.5 - 2.7$, and at the highest temperature ($T_0 = 985^0$F) neither effect is observed. For all temperatures, as the pressure ratio decreases the behavior of the screech becomes poorly defined.

The influence of temperature could enter through either the length or velocity characteristic of the screech mechanism. The characteristic length is directly related to the dimensions of the cellular shock structure. Since this structure results from pressure matching conditions, it should be independent of temperature. This was verified in schlieren photographs of the flow.

The characteristic velocity used by Powell in the prediction of the screech frequency is the ambient speed of sound. Strictly, no temperature dependence could enter. Considering the mechanism for the discrete frequency amplification suggested by Powell, it is reasonable to expect that the sound waves propagate upstream to the jet exit in the shear layer, not solely in the ambient air. The characteristic velocity would then be the sound speed in the shear layer. If the effective temperature is assumed to be the average of the jet exit static temperature and the ambient temperature, the prediction of

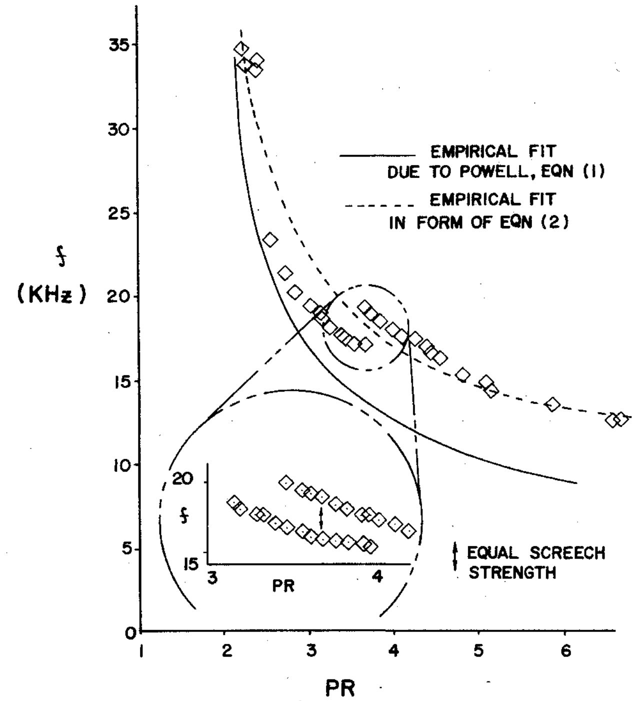

Fig. 1 Experimentally determined screech frequency vs PR including the apparent discontinuity.

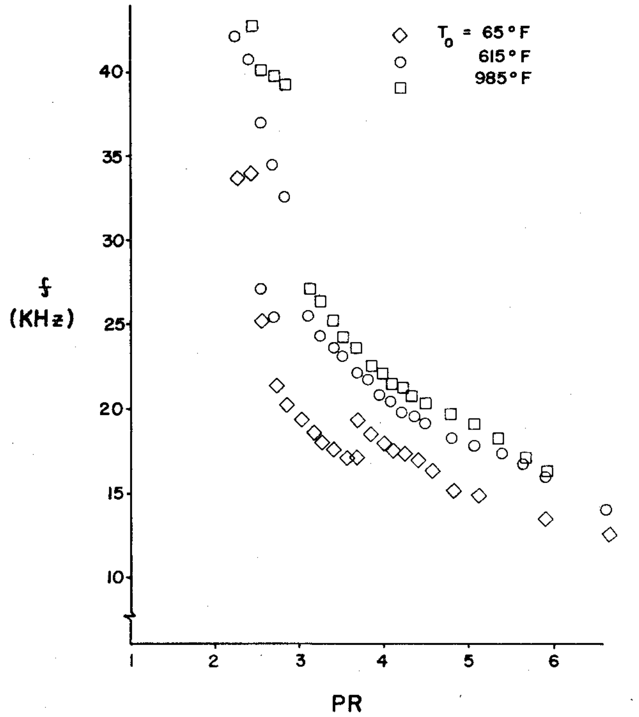

Fig. 2 Dependence of screech frequency on jet total temperature for $T_0 = 65^0$F, 615^{0}F, 985^{0}F.

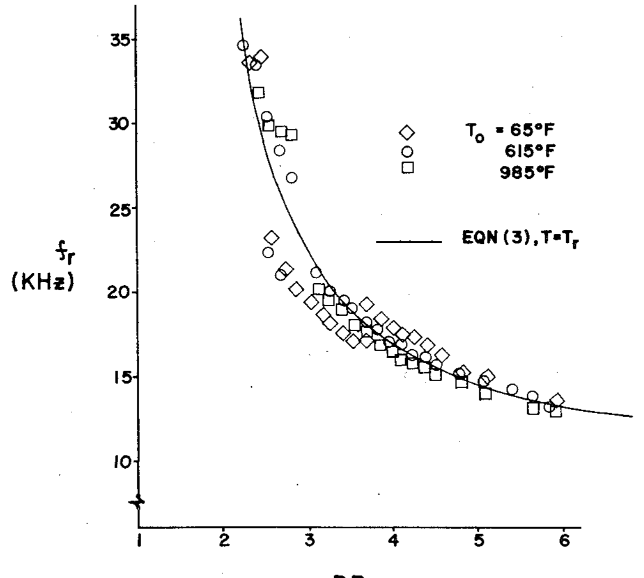

Fig. 3 Reduced screech frequency for $T_0 = 65^0$F, 615^{0}F, 985^{0}F, and $T_r = 65^0$F.

screech frequency can be written

$$f = K_4(c_{s\ell/d}) + K_5(c_{s\ell/d})/(\mathrm{PR} - \mathrm{PR}^*)^{1/2} \tag{3}$$

in which

$$c_{s\ell} \equiv [\gamma R \tfrac{1}{2}(T_{\mathrm{amb}} + T_e)]^{1/2}$$

where $c_{s\ell}$ = sound speed in the shear layer, T_{amb} = ambient temperature, T_e = jet exit temperature, γ = ratio of specific heats, R = gas constant for air. The screech frequencies emitted from two jets at different temperatures but equivalent pressure ratios and exit diameters are related

$$f_1/[\tfrac{1}{2}(T_{\mathrm{amb}} + T_e)_{T_1}]^{1/2} = f_2/[\tfrac{1}{2}(T_{\mathrm{amb}} + T_e)_{T_2}]^{1/2}$$

Thus the data plotted in Fig. 2 can be collapsed to a single curve by defining a reduced frequency which references the screech to a jet at an arbitrary total temperature

$$f_r = f_{T_0}[(T_{\text{amb}} + T_e)_{T_r}/(T_{\text{amb}} + T_e)_{T_0}]^{1/2} \tag{4}$$

where f_r = reduced frequency, f_{T_0} = actual frequency at T_0, T_r = reference total temperature. Figure 3 displays the reduced frequencies for the three total temperatures investigated and a reference total temperature, $T_r = 65^0$F. Use of Eq. (4) collapses the data to a band which is bound by the screech associated with $T_0 = 65^0$F. Since no simple temperature dependence can narrow these boundaries, the presented dependence is considered adequate. Equation (3) is also plotted on this figure with values: $K_4 = 8.0 \times 10^{-2}$, $K_5 = 0.40$.

Conclusions

This investigation has quantified the dependence of jet screech on temperature for an axisymmetric, sonic jet. The temperature changes vary the characteristic velocity which was found to be the sound speed in the shear layer. The empirical expression of Eq. (3) adequantly represents this dependence with constants $K_4 = 8.0 \times 10^{-2}$ and $K_5 = 0.40$. There are, therefore, three parameters which vary the screech frequency: jet pressure ratio, jet temperature, and jet diameter.

It was observed that an apparent discontinuity in frequency for an ambient temperature jet ($T_0 = 65^0$F) was actually a continuous transition - as the intensity at the lower frequency decreased, the intensity at a higher frequency increased. Such discontinuities were not observed in hotter jets, although related phenomena, such as multiple dominant frequencies, occurred at low pressure ratios.

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Hypersonic Incipient Separation on Delta Wing with Trailing-Edge Flap

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Introduction

RECENT investigations of trailing-edge flap control effectiveness on delta wings at hypersonic Mach numbers have indicated the complexity of the flow patterns associated with flap-induced boundary-layer separation.[1-4] Factors contributing to the complexity are the three-dimensional flow in the delta wing boundary layer and the effects of transition. Under such three-dimensional separated-flow conditions, reliable assessment of flap effectiveness and intense heating rates encountered at re-attachment on the flap pose serious design problems. These difficulties could possibly be overcome by providing larger flap area and reduced control deflections in order to avoid separating the flow, given the ability to predict incipient separation. However, little is known regarding incipient boundary-layer separation in three-dimensional flow; also, whether the extensive two-dimensional data available on wedge-induced separation could be utilized for this purpose needs to be clarified.

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Table 1 Test data on 75° delta wing with trailing-edge flap

Author	Facility	M	R/in.	L in.	Ref.
Rao (1970)	Imperial College Gun Tunnel	8.2	$0.22 \times 10^6 - 0.3 \times 10^6$	4.0,6.5	1
Davies (1970)	NPL Shock Tunnel	8.0	$0.12 \times 10^6 - 0.2 \times 10^6$	2.6,6.4	2
Keyes (1969)	NASA-LRC Blowdown Tunnel	6.0	$0.16 \times 10^6 - 0.7 \times 10^6$	8.0	3

This Note reviews the limited experimental data available on planar delta wings of 75°-swept sharp leading-edges, with full-span trailing-edge flap deflected into the windward flow (see Table 1). The local Reynolds number range between these investigations covered the laminar, transitional, and turbulent conditions (without the use of boundary-layer trips). A comparison of these results with two-dimensional data has led to some interesting conclusions regarding trailing-edge flap-induced incipient separation on delta wings.

Discussion

Incipient separation was determined by plotting the distance to separation X_s (obtained from pressure distributions or Schlieren photographs) against the hinge-line Reynolds number (R_L), for a fixed flap deflection (δ), and extrapolating to the hinge-line (i.e., zero separation length). An example is shown in Fig. 1, where data from the three sources are plotted for $\delta = 10°$, 20°, and 30°. The extent of separation on the delta wing at a given flap angle appears to follow qualitatively the well-known two-dimensional behavior as influenced by local Reynolds number (e.g., Ref. 5). Thus, an initial decrease in X_s with increasing Reynolds number, representative of laminar flow, is followed by a reversal of the trend with the onset of transition starting in the shear layer and progressing upstream to the attached flow. The data from different sources show good agreement even though the local Mach number on the windward surface ranged from about 4.5 to 7.5 due to varying angle of attack, indicating that transitional separation is dominated by Reynolds number and is relatively less sensitive to Mach number in the range encountered here.

Incipient separation data determined for the 75° delta wing are plotted in Fig. 2 as $\delta_i/\sqrt{M}$ vs R_L(δ_i = flap angle for incipient separation), a form that was previously found to correlate the two-dimensional turbulent as well as transitional data separately over a broad Mach number range.[6] The delta wing data, although few, suggest a distinctive correlation of their own, which offers interesting comparisons with the two-dimensional case. In the laminar regime, flap-induced incipient separation on the delta wing is postponed to larger flap deflection (almost by a factor of two) for given local-flow Mach and Reynolds numbers. The sudden rise of $\delta_i/\sqrt{M}$ from the laminar towards the turbulent level parallels the two-dimensional trend, although occurring earlier, as may be anticipated from the well-known reduction in transition Reynolds number due to leading-edge sweep. The Reynolds number range over which delta wing incipient separation displays transitional behavior corroborates the transition Reynolds number for this wing obtained in the same test facility.[7] Turbulent incipient separation on the delta wing appears to be practically indistinguishable from the two-dimensional data.