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SUPERSONIC JET SCREECH: HALF-CENTURY FROM POWELL TO THE PRESENT

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Under certain conditions, shock-containing jets produce an intense tone referred to as screech. Screech was discovered about half a century ago by Alan Powell in England. Here I recount developments in supersonic jet screech — from Powell's first observation in 1951 to now. During this period more than 200 papers have been published — many offering only incremental advances. This paper provides a concise screech resource including a historical perspective, a summary of recent developments and a critical assessment of the state of the art. Topics include modulation of instability waves by shocks, shock-cell models and screech frequency prediction models, unsteady shock motions and clues about their role in shock noise generation. Also, detailed nearfield measurements and computer simulation methods now available are discussed. However, despite the advances, screech amplitude prediction remains an elusive but increasingly important goal not only due to concerns about sonic fatigue failure of aircraft structures but because knowledge gained by the study of screech can be applied to a variety of resonant flow situations, including jet impingement, cavity resonance, and closed-loop active flow control.

1. INTRODUCTION

Under certain conditions imperfectly expanded jets produce a discrete tone referred to as screech. The study of supersonic jet screech began in the early 1950s at the University of Southampton in England. Powell took the first set of photographs of a screeching jet in 1951 (published later in 1953, Powell [1]) using an elementary home-made Schlieren system with chemistry stands on a table. For the small nozzles that Powell used ($0{\cdot}7 \times 0{\cdot}118$ in), the screech frequency was beyond the range audible to the human ear and since high-quality microphones were not easily available at that time, the discovery was based solely on schlieren flow visualization. Powell's careful scrutiny of the photographs revealed an asymmetric disturbance pattern in the two-dimensional jet, and he also observed sound waves

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propagating upstream. Later, it will be shown how this simple experiment provided ideas for the entire set of physics associated with screech. Powell [1, 2] then explained screech as follows: "The passage of an alternately disposed disturbance (or eddy) system gives rise to sound on traversing the regularly spaced shock wave system of the jet, the interference being such that a powerful emission takes place in the upstream direction. On passing the orifice the sound waves give rise to embryo disturbances". Thus, a resonant feedback loop develops and continues. Although there has been considerable progress in understanding details of screech, many important issues remain unresolved.

Almost 50 years after Powell's discovery, screech still plays a critical role in the design of advanced aircraft because it can cause sonic fatigue failure. Such failures have been observed before on the British Aircraft Corporation's VC-10 and on the F-15 and B1-B of the United States Air Force. It is now well known that twin-jet plumes on aircraft can couple, producing very high dynamic pressures in the inter-nozzle region, which in turn can cause sonic fatigue of external nozzle flaps.

Figure 1 shows a schematic diagram of the screech process and associated phenomena. Four key mechanisms responsible for screech are illustrated in Figure 1: (1) instability wave growth in a shock-containing supersonic jet, (2) instability–shock interaction, (3) acoustic feedback, and (4) receptivity processes (coupling of hydrodynamic and acoustic disturbances) occurring in the vicinity of the nozzle exit. The relative dominance of processes in the interdependent sequence (1–4) has eluded researchers for many years. Finally, with advances in computers and computational techniques, screech has emerged as a challenging test case for numerical simulations. The objective of this brief review is to (a) provide a resource for those working on screech, (b) assess our current understanding of screech, and

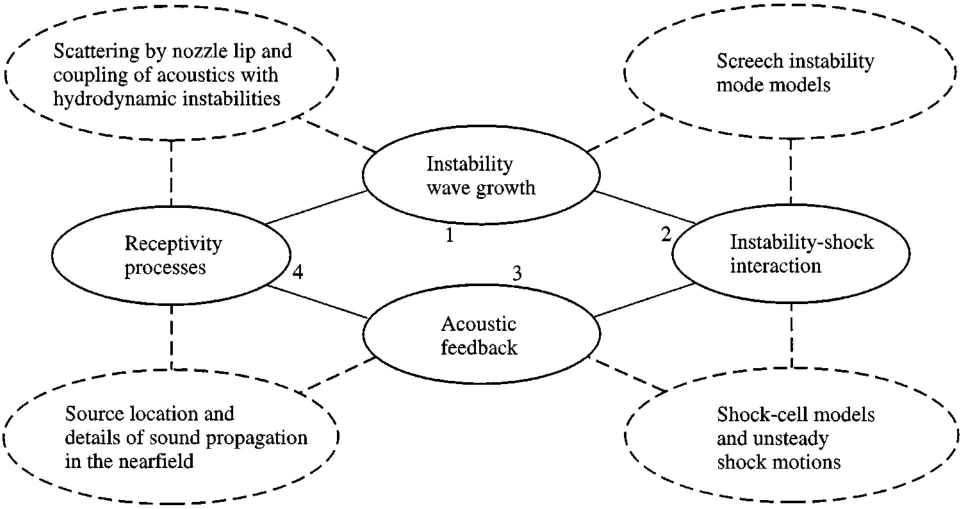


Figure 1. Schematic diagram of resonant screech loop (solid lines) and associated phenomena (dashed lines).

(c) raise critical issues that are most relevant in our quest to attain a screech amplitude prediction tool.

1.1. ORGANIZATION OF THIS BRIEF REVIEW

This brief review consists of six sections after the introduction. (2) Chronology of research on jet screech. (3) Instability waves of jets with shock cells. (4) Shock-cell models and screech frequency prediction. (5) Characterization of feedback. (6) Practical applications involving screech. (7) Computer simulations of screech. Section 2 covers the amplitude and phase criterion proposed by Powell (2.1) and the proliferation of screech research from the 1950s to the 1970s (2.2). Section 3 includes a description of the various screech instability modes (3.1) and the non-linear growth of disturbances in a screeching jet (3.2). Section 4 discusses models for shock-cell spacing (4.1) and screech frequency prediction (4.2). Screech amplitude dependence on shock structure, strength, and unsteadiness is covered in section 4.3. Section 5 considers new information on the details of the near field (5.1), feedback from localized single shock-wave emissions (5.2), and the effect of lip thickeners and reflective surfaces (5.3). Section 6 illustrates practical problems involving screech such as the coupling of twin jet exhaust (6.1), screech from nozzles of non-uniform geometry (6.2) and the use of screech for enhanced jet mixing (6.3). Recent developments in simulating screech are discussed in section 7, which is followed by concluding remarks.

2. CHRONOLOGY OF RESEARCH ON JET SCREECH

2.1. AMPLITUDE AND PHASE CRITERIA PROPOSED BY POWELL

Powell's [1–4] pioneering study of both two-dimensional and circular jets suggested a model that yielded formulae for the screech frequency and directivity. One important issue then was how to explain the schlieren observations that the noise radiation was most intense towards the nozzle. The observed directivity appeared to contradict the notion that the interaction between the jet instability and the shock cells produced monopoles at the jet edges. Powell resolved this apparent anomaly by modelling the sources as a phased array of regularly spaced monopoles with directionality dependent on the phase difference between the sources.

Many researchers have missed the fact that two criteria are embedded in Powell's theory. (1) The phase criterion requires that the travel time for the convection of downstream travelling hydrodynamic disturbances plus the time taken by the upstream travelling acoustic disturbances sum up to an integral number of screech cycle periods. A more sophisticated version of the phase criterion also accounts for the time delay associated with the emission of sound after shock-vortex interaction and the time delay associated with the triggering of embryonic hydrodynamic waves at the nozzle exit by upstream propagating acoustic disturbances. In very special circumstances these delays could approach zero. (2) The amplitude criterion requires the sound directivity to be maximum in the upstream direction ($\alpha = 180°$ measured from the downstream direction). In other words, we expect waves originating from various downstream sources to reinforce at the nozzle exit. According to Powell [3] both criteria need to be satisfied simultaneously. For a more detailed discussion of the amplitude and phase criteria an interested reader could consult Powell's [3] paper on edge tones and associated phenomena.

Powell [1] also derived formulae for the directionality of the fundamental and harmonic tones by considering either three or four stationary sources of equal strength and considering the phasing between adjacent sources. Powell's [1] formulae that give the directivity pattern, D, of the main lobes are

$$D_f = \tfrac{1}{3} + \tfrac{2}{3}\cos[2\pi(s/\lambda_c)(1 - M_c\cos\alpha)], \tag{1}$$

$$D_h = \tfrac{1}{3} + \tfrac{2}{3}\cos[4\pi(s/\lambda_c)(1 - M_c\cos\alpha)], \tag{2}$$

for the fundamental and harmonic frequencies (subscripts f, h), respectively. Note that s is the shock-cell spacing, α is the angle measured with respect to the downstream direction, and M_c and λ_c are the convective Mach number and wavelength of the disturbance, respectively. Note that equation (1) attains a maximum when $\alpha = 180°$. In contrast, the harmonic exhibits a narrow lobe that peaks at 90° if $s/\lambda_c = 1$. Typically, this ratio is not 1 and so the harmonic is observed to peak at an angle of a little less than 90°.

Powell [2] provided a simple formula for calculating the screech frequency, given by

$$f = \frac{U_c}{s(1 + M_c)}, \tag{3}$$

where f is the screech frequency, U_c is the convective speed of the hydrodynamic disturbance, s is the shock spacing, M_c is the convective Mach number (U_c/c), and c is the speed of sound in the ambient. Note that equation (3) can be derived from equation (1) by postulating that the radiation is near a maximum in the upstream direction for maximum feedback (amplitude criterion). Simple as it may seem, the formula depends on accurately determining the convective speed of downstream propagating structures. Non-uniformity in acoustic feedback (speed of sound not being constant) is less important but may need to be considered. Finally, there is also the issue of what shock spacing to consider if non-uniformities in shock spacing arise.

Powell [4] also advocated viewing the resonant screech loop as a limit cycle involving four factors: (i) instability wave growth (q), (ii) shock–instability wave interaction (η_s), (iii) feedback efficiency (η_t), and (iv) stream disturbance creation efficiency (η_d). Factor (iv) is now known as receptivity. Powell [4] gave the limit-cycle condition as

$$Q\eta_s\eta_t\eta_d = 1. \tag{4}$$

Early work	
Powell	[1–4]
Lassiter and Hubbard	[5]
Merle	[6]
Davies and Oldfield	[7, 8]
Poldervaart *et al.*	[9–12]
Westley, Woolley, Chan, Lee	[13–23]

Work done in the former Soviet Union	
Sedel'nikov	[24–26]
Anufriev *et al.*	[27]
Glaznev	[28]
Bikart	[29]
Glaznev *et al.*	[30]
Sokolov and Uskov	[31]

More recent work	
NASA Langley—Seiner, Norum, Ponton, Shearin	[32–45]
McDonnell Douglas—Kibens, Wlezien, Zliz, Cain, Bower	[46–54]
Lockheed Georgia—Ahuja, Lepicovsky	[55–61]
Penn. State University—Morris, McLaughlin, Hu	[62–67]
Florida State University—Tam, Krothapalli	[68–79]
Naval Air Warfare Centre—Gutmark	[80–81]
USAF, Wright Lab—Shaw, Walker	[82–85]
NASA Lewis—Raman, Taghavi, Rice, Panda, Zaman	[86–106]
University of Houston—Powell, Lin	[107–114]
Japan—Kaji, Umeda, Ishii	[115–120]
Naval Research Lab—Kolbe, Kailasanath, Boris	[121–123]
Ohio State University—Scott	[124]
Stanford University—Manning, Lele	[125]

Figure 2. Chronology of research on jet screech.

2.2. THE PROLIFERATION OF SCREECH RESEARCH FROM THE 1950s TO THE 1970s

Since a brief review cannot include a detailed account of all contributions, references [1–125] are ordered and categorized chronologically in Figure 2. (For a much longer and more detailed review of screech, see Raman [126].) Powell's [1, 2] discovery of screech was followed by the work of Lassiter and Hubbard [5] and Merle [6]. Powell [2] had identified four discrete frequency stages (A–D) in a round jet. Merle [6] extended Powell's work and studied the staging of circular jets using stroboscopic lighting and found that there were two parts to stage A, which we now call A1 and A2. She also noted that A1 was unstable, A2 stable, B very unstable, C very stable, and finally stage D was unstable and not always visible. Davies and Oldfield [7, 8] were the first to use two microphones on either side of the jet to characterize the modes as being axisymmetric (A1, A2), sinuous (B), and helical (C). However, mode D resisted classification. Powell [2] had also noted that flapping modes in the jet precessed in one direction or the other rather unpredictably. Recent studies on the staging of screech are discussed in section 3.1.

Poldervaart and co-workers, who conducted a very thorough flow visualization study at the University of Eindhoven in the Netherlands [9–12], produced several films that photographically documented the feedback loop of screeching jets and the effect of reflectors and externally generated pulses on the jet.

The group at the National Research Council of Canada (Ottawa) including Chan, Lee, Westley, and Woolley [13–23] also contributed significantly. A series of papers and movies by Westley and Woolley [13–20] described the instantaneous nearfield maps of the sound pressure levels at various phases for jets screeching in the axisymmetric and spinning modes. They also described the complex acoustic feedback and shock unsteadiness. Chan [21, 22] provided an alternative explanation of screech sources by suggesting that they could be thought of as dipoles instead of the monopoles considered by Powell [1].

Soviet screech work started late, but its researchers elicited details of the growth of instability waves in supersonic jets, the modulation of instability waves by shocks, and the effect of temperature on screech many years before these were recognized in the West. Sedel'nikov [24–26] provided a theoretical explanation of screech. He also calculated the growth of instability waves (which he called dispersion waves) in supersonic jets. Subsequently, Anufriev *et al.* [27] obtained detailed data to define the frequency versus Mach number curve for a round jet. They noted that preheating the air jet lowers the intensity of screech and increases the frequency. Glaznev [28] found that the discrete tone perturbations were three dimensional for a round jet and that their amplitude changed abruptly at the shock locations (now known as modulation of instability waves by shocks). Bikart [29] studied screech tones from nozzles with design Mach numbers of 1, 1·4, 2, 2·5, and 3 for various levels of over- and underexpansion. He measured the screech amplitudes and frequencies for all conditions, and his screech frequency versus Mach number curve compared favorably with the theory described by Sedel'nikov [24–26].

3. THE INSTABILITY OF JETS WITH SHOCK-CELLS

3.1. SCREECH MODES

A jet undergoing screech exhibits various oscillation modes that depend on nozzle geometry. Both circular and rectangular jet modes will be described in this section. Very detailed studies on screech modes A–D in circular jets were conducted by the group at NASA Langley Research Center [32–34, 39–41, 45]. A comparison of the data from various researchers on the wavelength of the screech stages was provided by Norum [40]. Norum and Shearin [41] documented the amplitudes of the various screech stages. There are distinct jumps in frequency between modes A and D and the peak screech amplitude is also mode dependent. Recent contributions include the study by Powell *et al.* [110] that revisits the staging problem using modern instrumentation. They provide a detailed account of stages A–D and some very interesting results on the frequency ratio of modes C and B versus nozzle pressure ratio. Despite numerous papers on the topic, no one to date has offered clear explanation for the mode jumps.

In rectangular jets most researchers had noted a strong antisymmetric jet oscillation mode; the sound produced by the jet was out of phase on either side (see Powell [1], Poldervaart *et al.* [10, 11], Krothapalli *et al.* [78], Shih *et al.* [127], and

Gutmark *et al.* [80] among others). More recently, the symmetrical mode has been observed in rectangular jets. Gutmark *et al.* [80] noted that a rectangular jet at Mach numbers slightly above choking exhibited a symmetric mode and that this mode switched to an antisymmetric mode at a fully expanded Mach number of 1.15. Subsequently, Kaji and Nishijima [115], Suda *et al.* [116], and Nishijima and Kaji [117] proved that rectangular jets are capable of sustaining both symmetric and asymmetric modes. Similar observations of symmetrical modes in edgetones and rectangular jet screech were made by Lin and Powell [114].

3.2. THE NON-LINEAR GROWTH OF DISTURBANCES IN A SCREECHING JET

The first step necessary for initiating the screech loop is instability wave growth. Instability waves growing in shock-containing flows exhibit unique characteristics. Westley and Woolley's [15–17] schlieren movies showed that contrary to the accepted belief that disturbances travel at a constant speed, the density gradients in time-resolved shadowgraph measurements accelerated between shocks and decelerated as they approached a shock. The exponential growth of instability modes often encountered in shear layers of jets is significantly altered in shock-containing jets. Several factors could be responsible for the acceleration and deceleration of the instability wave. First, the shock/expansion train in an imperfectly expanded jet produces an alternating convergent and divergent flow

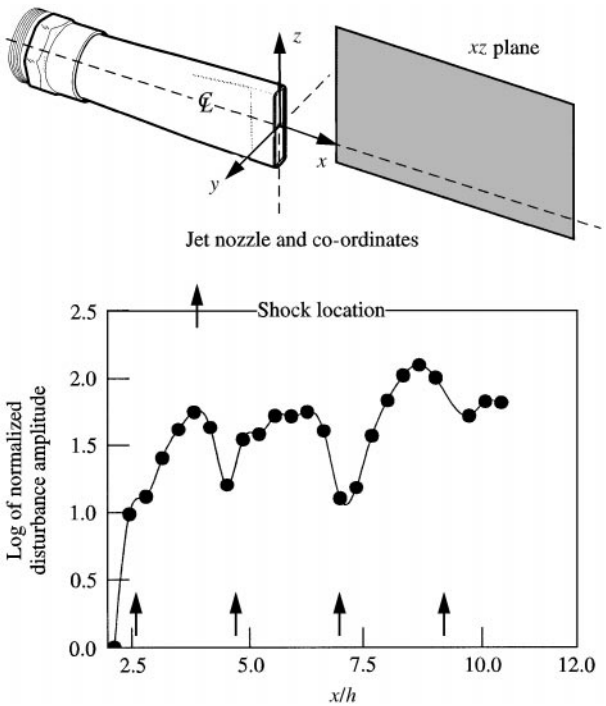


Figure 3. Evidence of instability wave modulation by shocks. Data of Raman and Rice [88] for a rectangular jet, $M_j = 1{\cdot}44$.

boundary. Since the supersonic mean flow accelerates and decelerates as it negotiates the convergent– divergent "channel", it is reasonable to expect that the disturbance velocity would also do the same. Second, shocks modulate the instability waves. This modulation of the instability wave is clearly visible in the data of Raman and Rice [88] (Figure 3). In their experiments, the streamwise evolution of the dominant screech instability mode and its harmonics was obtained by traversing a hot-film probe along the $M = 0{\cdot}4$ line in the shear layer. Figure 3 reveals that the evolution is highly non-linear, and it is difficult to identify a streamwise region where sustained exponential growth is consistent with linear theory. The shocks also significantly modulate the velocity fluctuation amplitudes. These modulations are indicated by the dips before the shocks and a subsequent recovery of the amplitude downstream of the shock. Thus, the data of Figure 3 qualitatively characterize the coherent eddy–shock interaction as observed on the $M = 0{\cdot}4$ line.

4. SHOCK-CELL MODELS AND SCREECH FREQUENCY PREDICTION

4.1. SHOCK-CELL MODELS

The second step in the resonant screech loop is the interaction between the instability wave and the shock cells. Modelling shock-cell spacing plays a key role in determining the frequency of screech. Prandtl (as quoted in Pack [128]) determined the cell length of a supersonic round jet using a linear inviscid analysis. Later this came to be known as the Prandtl model (see Pack [128]). Powell [112] pointed out that the Prandtl wavelength is smaller than the length of the repetitive diamond pattern of choked jets. Tam *et al.* [68] constructed a multiple-scales shock-cell model for a linearly perturbed supersonic circular jet. Their results compared well with the measurements of Norum and Seiner [39].

Considerable progress has been made in developing estimates of the gross features of the cell length of rectangular supersonic jets that are linearly perturbed [72, 62, 63]. In Tam's model, the shock-cell system in the jet column was bounded by a mixing layer that was approximated by a vortex sheet (following the ideas of Prandtl; see Pack [126]), and he solved the problem by an eigenfunction expansion. The solution to the eigenvalue problem yielded explicit shock-cell spacings. The solution to the shock-cell problem was also provided by Morris *et al.* [63]. The important difference between Tam's [72] work and Morris's work is that Morris *et al.* [63] used the boundary element method for accommodating nozzles with arbitrary cross-sections instead of an eigenfunction expansion. By both methods, the vortex sheet model provided an average shock spacing that was a good first approximation of the measured shock-cell spacing. This is a very interesting result considering that a linearly perturbed supersonic jet does not have the same structure as a choked jet. The shock-cell spacings obtained using the methods of Tam [72] and Morris *et al.* [63] are compared with the experimental data of Raman and Rice [88] in Figure 4(a).

The above theories effectively predict the gross shock-cell features, including the average shock-cell spacing and the shock-associated noise intensity of jets with

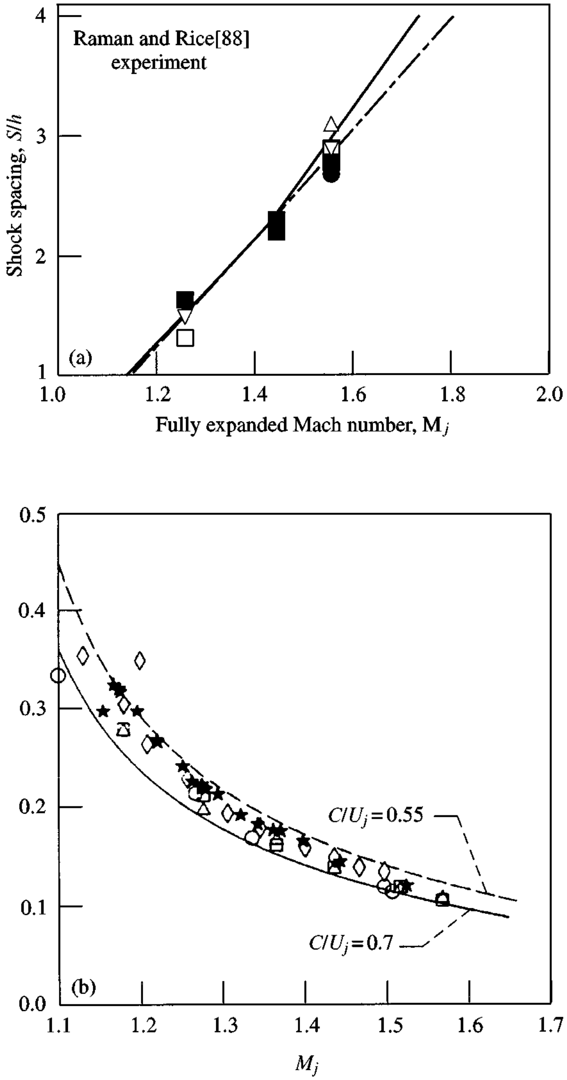


Figure 4. Shock spacing and screech Strouhal number characteristics for rectangular jets: (a) shock spacing versus fully expanded jet Mach number (from Raman and Rice [88]). Experimental data, □ shock 1; ▽ 2; ● 3; ■ 4; △ 5; - - - Computation, b/h = 5·83 Morris *et al.* [63]; —— Analytic solution, Tam [72], (b) screech Strouhal number versus fully expanded jet Mach number (from Shih *et al.* [127]). Experimental data, □ Krothapalli *et al.* [78], AR = 10; △ Krothapalli *et al.* [78], AR = 16·7; ◇ Powell [1,2], AR = 5·83; ○ Gutmark *et al.* [80], AR = 3; ★ Shih *et al.* [127], AR = 4; - - - Theory, Tam [72], Large AR.

weak (linear) shocks. At more severe levels of underexpansion, especially after the formation of the Mach disk, the shock-cell structure, strength, and spacing exhibit variations, some of which show discernable trends. The goal would be to stimulate the development of a second-generation model that captures the non-uniform variations in shock spacing, strength, and structure. Incorporating such details could aid in the production of a screech prediction model.

4.2. SCREECH FREQUENCY PREDICTION

The previous section described how we can determine the wavenumber of the shock-cell system, after which it is relatively straightforward to estimate the screech frequency. Tam *et al.* [69] observed that the acoustic waves radiating to the nozzle lip region were confined to a narrow frequency band if they were generated by the interaction between the large-scale instability waves and the quasiperiodic shock-cell structure of a supersonic jet. The band is centered on frequency f_p given by

$$f_p = \frac{u_c k}{2\pi[1 + (u_c/a_\infty)]}, \tag{5}$$

where u_c is the convection or phase velocity of the instability waves, a_∞ is the ambient sound speed, and k is the wavenumber of the shock-cell structure. Note that substituting $k = 2\pi/s$ (where s is the shock-cell spacing in equation (5) gives equation (3).

For circular jets the screech frequency formula cannot predict the A–D mode jumps. However, for rectangular jets the linear model is very accurate, and the screech frequency can be easily predicted by taking k in equation (5) to be the wavenumber of the lowest waveguide mode ($n = 1$, $m = 1$)

$$k = k_{11}\left(\frac{1}{b_j^2} + \frac{1}{h_j^2}\right)^{1/2} \frac{\pi}{(M_j^2 - 1)^{1/2}}, \tag{6}$$

where b_j and h_{j} are the fully expanded large and small nozzle dimensions, respectively. Shih *et al.* [127] compared calculated and measured values and is shown in Figure 4(b). Note that Tam's [72] theory with $U_{\mathrm{c}} = 0{\cdot}55$ fits the experimental data better than $U_{\mathrm{c}} = 0{\cdot}7$.

The above formulae do not account for the effect of temperature and flight. Jet temperature affects screech frequencies since U_{c} is higher for hot jets. Tam *et al.* [69] calculated the screech frequency of hot jets, and their results agreed with the hot jet measurements of Rosfjord and Toms [129] and Krothapalli *et al.* [79]. The effect of flight velocities on screech frequency was studied by Bryce and Pinker [130], and Tam [73]. Several researchers, including Norum and Shearin [41] and Krothapalli *et al.* [79], found reasonable agreement between Tam's formula and their experimental data.

4.3. SCREECH AMPLITUDE DEPENDENCE ON SHOCK STRUCTURE, STRENGTH, AND UNSTEADINESS

An earlier section showed that it is easy to estimate the screech frequency when we know the shock-cell spacing; however, the relationship between shock strength and screech amplitude is far from clear. The data of Raman [92] clarify that the connection between shock strength and screech amplitude is very weak. Shocks are necessary to produce screech, and a certain shock strength is required to produce strong screech, but a further increase in the shock strength has no effect on screech amplitude. A final point of interest is that at high jet Mach numbers, screech ceases to exist even when the shocks are very strong. Thus, shock strength only plays a role in initiating screech or in destabilizing a particular screech mode in jets with complex shock-cell structures (see Raman [92]), but otherwise shock strength and screech amplitude remain uncorrelated.

The steady shock-cell picture for a jet has been quite well known for some time. However, the unsteady motion is intimately connected with the screech source. Westley and Woolley [13–16] studied the details of unsteady shock motions for round jets from their schlieren movies. They were the first to note double shocks or infant shocks in a circular jet. They documented the disturbance and shock motions during a screech cycle and the tilt angle of shock bases during a screech cycle. However, their unsteady shock motion studies were not pursued further for many years. Recently, Suda *et al.* [116], Kaji and Nishijima [115], and Panda [103] resumed progress in understanding unsteady shock motions.

Suda *et al.* [116] provided a very detailed explanation for unsteady shock motion for a two- dimensional jet. They used a laser schlieren system to observe a travelling shock wave in the third shock cell. If we look at the third shock cell of a two-dimensional jet (see Figure 5), the travelling wave A–B rotates around the point B and sweeps downstream [Figure 5(a, b)]. At the end of half a cycle, the edge of the travelling wave A reaches the downstream end of the cell and coalesces into the end of the third cell [Figure 5(c,d)]. By this time a new travelling wave A′–B′ originates, and the rest of the cycle repeats in a similar fashion. Note that now the travelling wave A′–B′ rotates around point A′ and sweeps downstream [Figure 5(d, e)] and again coalesces into the end of the third cell. Based on this explanation,

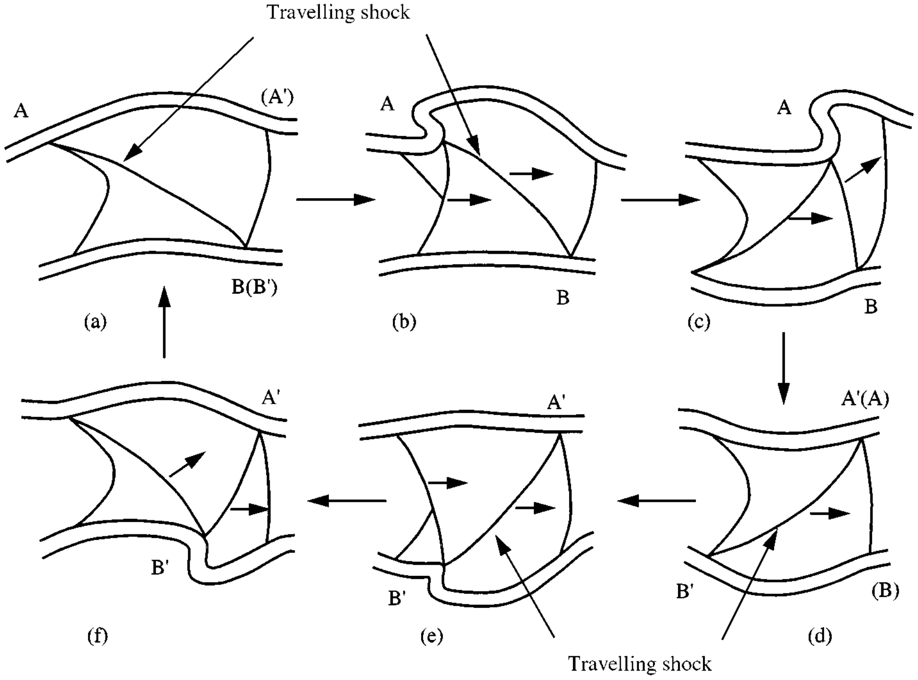


Figure 5. Dynamic motion of travelling shock in the third shock-cells (from Suda *et al.* [116]).

Suda *et al.* [116] suggested that this travelling shock wave is the actual source of screech.

Panda [103] made phase-averaged measurements of the shock motions using a laser shock detection technique. Typical measurements for the motion of the third shock show that as time progresses, the shock center moves downstream, and a weaker shock appears upstream. As time passes, the upstream shock becomes stronger, and the downstream shock weakens. The process then repeats itself.

5. CHARACTERIZATION OF FEEDBACK

5.1. DESCRIPTION OF THE NEAR FIELD

As mentioned in the introduction the final steps in the screech loop require the sound-generated downstream to propagate to the nozzle lip (feedback) and couple with the hydrodynamic disturbances in the shear layer (the process of receptivity). Feedback and receptivity are clearly important because although similar processes (with the exception of feedback to the nozzle lip) produce screech and broadband noise, we can predict the amplitude of the latter but prediction of the former remains an elusive goal. A description of the acoustic near field is very crucial for understanding of feedback and receptivity processes.

Westley and Woolley [13–16] were the first to document details of the acoustic near field. The distinctive radiation pattern displays sound pressure levels that vary from 160 dB near the jet boundary to about 130 dB at a radial distance of 6D from the jet. Their data also illustrate the emergence of a standing-wave pattern. Westley and Woolley [13–16] suggested that the standing wave may result from the interaction between downstream-propagating hydrodynamic waves and upstream-propagating acoustic waves. Further, reflection from an upstream flange could also produce an acoustic–acoustic standing wave that may also influence the former type of standing wave. It should be noted that standing-wave formation is not specific to a shock-containing screeching jet. Lepicovsky and Ahuja [59] showed that a standing wave exists in the near field even for a subsonic edgetone situation. Westley and Woolley's [13–16] data also show lobes of high sound pressure levels between shocks that extend out normal to the jet with the strongest maxima occurring at shocks 3 and 4. Westley and Woolley [19] also documented the instantaneous pressure distributions in planes perpendicular to the jet axis that displayed the spiraling motion of the near-acoustic field during spinning mode screech.

Detailed phase-averaged measurements by Panda [104] show the downstream propagating hydrodynamic disturbances as well as upstream- and downstream-propagating acoustic waves for a round jet at $M_j = 1{\cdot}19$. In a movie based on Panda's [104] data, the upstream-propagating acoustic waves exhibited a pause-and-go feature as they negotiated the standing wave. Similar data on the phase-averaged acoustic near field was reported by Raman *et al.* [94] for a rectangular jet (aspect ratio = 5, $M_j = 1{\cdot}8$) with an upstream reflector located at a position that maximized screech. Although standing waves were observed by Davies and Oldfield [7, 8], Westley and Woolley [13–16], Chan [21], and Rice and

Taghavi [98], their relationship to the screech frequency was only recently reported by Panda [104].

Panda [104] suggested that a standing wave pattern is expected with a resultant wavenumber $k_{sw} = k_s + k_h$. If k_h is associated with the hydrodynamic fluctuations of wavelength $\lambda_h (k_h = 2\pi/\lambda_h)$, k_s with sound waves of wavelength λ_s, and k_{sw} with the standing waves of wavelength L_{sw}, then one can represent L_{sw} as $1/L_{sw} = 1/\lambda_s + 1/\lambda_h$. Since $\lambda_s = c/f_s$ and $\lambda_h = u_c/f_s$ where c is the ambient speed of sound, f_s is the screech frequency and u_c is the convective speed of the hydrodynamic disturbances, a frequency formula can be written that resembles Powell's [1, 2] equation with the wavelength of the standing wave replacing the shock spacing in Powell's [1,2] original formula. Panda *et al.* [105] demonstrated that the above relationship also applies to rectangular and elliptic jets.

5.2. FEEDBACK FROM LOCALIZED SINGLE SHOCK-WAVE EMISSIONS

For screech from rectangular jets, some striking points can be made regarding the concept of an equivalent source and a spatial shift in this source with increasing Mach number. The phase data of Figure 6 indicates that a null-phase region exists (in the y direction) where the phase does not change for both cases. However, the null region is larger for the $M_j = 1{\cdot}75$ case. The data and analysis in Figure 6 indicate that this null region and phase variation can be easily modelled. The phase variation model invokes several assumptions. First, the multiple sources of screech are replaced by a single "equivalent" source. Second, the source is located at $y = h/2$, where the tip of the shocks interacts with the coherent eddies to produce sound. Finally as shown in Figure 6(a), it is assumed that the source radiates as a monopole. The simple theory is compared with experimental data in Figure 6(b). The best match is obtained if the source is located at the third shock for $M_j = 1{\cdot}45$ and at the fourth shock for $M_j = 1{\cdot}75$. The screech source shift from the third to the fourth shock occurs because, at higher M_j, the amplification of instability waves at the screech frequency is lower; however, the wave still grows but peaks further downstream, thus producing the downstream source shift. An interesting question arising from the data of Figure 6: if feedback occurs from sound produced at a single source without interference from adjacent sources (i.e., without upstream amplification), then how can one explain the strong upstream directivity of screech?

Clearly, if one source dominates, then the directivity emphasis is weak or even non-existent, so the amplitude criterion drops out for selecting screech frequency, and only the phase criterion applies. Screech now is analogous to the edgetone. Thus if the distance, h, from the nozzle exit to the edge is replaced by $h = (N + p)s$, where N is an integer, p is a number less than 1, and s is the shock spacing, then the edgetone formula is equivalent to the screech frequency formula. In a recent keynote lecture, Powell [113] also suggested that feedback efficiency, η_t, plays a critical role in screech amplitude prediction. He provided examples where he correctly predicted the slope and constant amplitude of screech over a range of Mach numbers, and the results compared reasonably well with the experimental data of Raman [92].

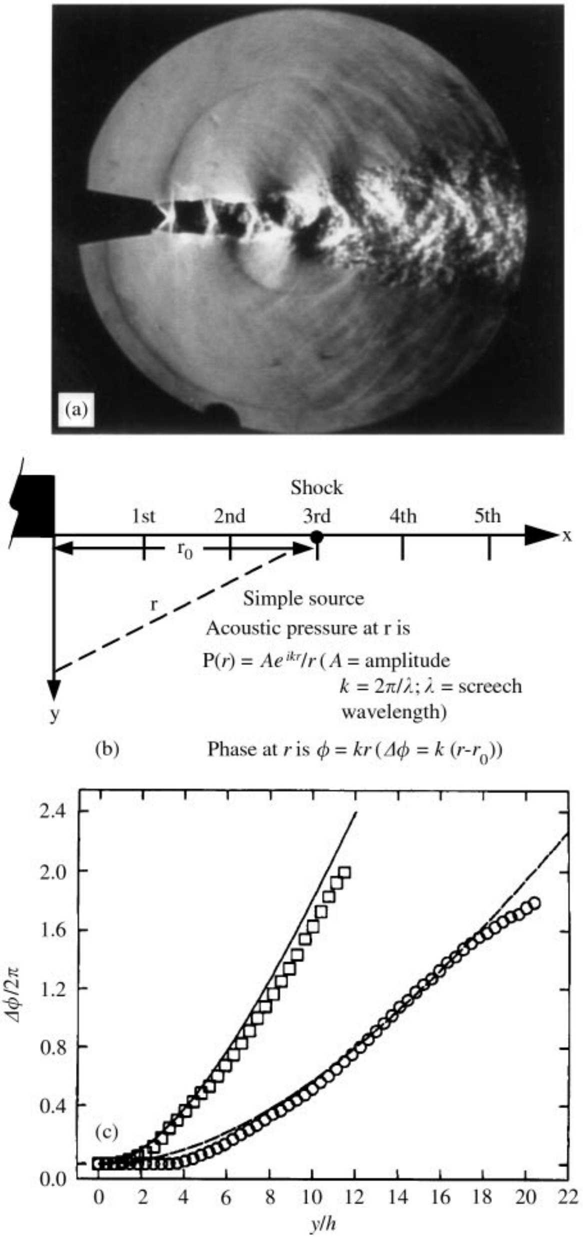


Figure 6. Source location and evidence of screech source shift with Mach number. (a) Schlieren photograph of a feedback shock originating at the third shock-cell during intense screech at $M_j = 1{\cdot}4$ (photograph taken during the experiments of Raman [92]). (b) Schematic diagram describing relative phase calculation (from Raman [92]). (c) Comparison of experimental and theoretical values of relative phase in the transverse (y) direction, $x/h = 0$, $z/h = 0$. (from Raman [92]). □ Expt, $M_j = 1{\cdot}45$; ○ Expt, $M_j = 1{\cdot}75$; —— Calculated, $M_j = 1{\cdot}45$ (Source located at third shock); – – – Calculated, $M_j = 1{\cdot}75$ (Source located at fourth shock).

Recently, Westley [20] suggested that the emission of a feedback shock can be thought of as being due to "eddy whiplash". He provided physical reasoning that an eddy suffers "whiplash" when it is retarded and accelerated through the shear region where the shock reflection point is located. Interestingly, around the same time, Krehl *et al.* [131] considered shock emission from the cracking of a whip. They found that the tuft at the tip of the whip accelerated from $M = 1{\cdot}1$ to $2{\cdot}19$ within a distance of 45 cm, this producing a "whip-tip" shock. It remains to be seen how valid the analogy of "whip-tip" dynamics is to screech and if we can consider sound as being produced by "shock-induced eddy whiplash". What has remained unresolved is why circular jets and rectangular jets of low aspect ratio do not display such localized single shock wave emissions observed in two-dimensional jets.

5.3. EFFECT OF LIP THICKENERS AND REFLECTIVE SURFACES

Surfaces in the near field such as a thick nozzle lip or a plenum flange significantly alter screech tones. The presence of such reflective surfaces could perhaps account for the differences in screech amplitudes observed from laboratory to laboratory for nozzles of similar design.

The nozzle lip thickness effect was first observed by Powell [4] and briefly mentioned by Merle [6] (as noted by Powell *et al.* [110])). Ponton and Seiner [44] studied the effect of lip thickness for a choked circular jet from a convergent nozzle. Their data showed that although screech ceased to exist at an M_j of 1·6 when the lip thickness was $t/D = 0{\cdot}2$, it persisted up to $M_j = 1{\cdot}9$ when t/D increased to 0·625. However, the lip thickness effect in their experiments is further complicated by a mode switch from C to D. Raman's [92] results for rectangular jets support the findings of Ponton and Seiner [44]. Figure 7 shows schlieren photographs and spectra for jets with and without nozzle lip thickeners. The addition of a lip thickener induces a large sinuous oscillation in the flow and increases the screech sound pressure level by 23 dB.

Reflective surfaces near the nozzle exit plane also enhance screech tones from supersonic shock-containing jets. Notes on how an upstream reflector affects screech appear in Powell [4], Poldervaart *et al.* [11], Harper-Bourne and Fisher [132], Nagel *et al.* [133], and Norum [42]. Powell [4] noted that the reflective surface area in the nozzle plane influences screech significantly. Subsequently, Poldervaart *et al.* [11] demonstrated that reflective surfaces and baffles placed both upstream and downstream of the nozzle exit can affect screech dramatically. Nagel *et al.* [133] used an upstream reflector to cancel jet screech. When the reflector was located at odd multiples of $\lambda_A/4$ (where λ_A represents the acoustic wavelength) from the nozzle exit, screech was minimized. They suggested that the cancellation may be occurring because the reflector had set up a standing wave with a pressure minimum at the jet exit plane. Norum [42] also studied the effect of a reflecting surface and its size requirements: a properly designed reflector can destroy the feedback cycle inherent to screech production.

6. PRACTICAL APPLICATIONS INVOLVING SCREECH

6.1. SCREECH COUPLING IN TWIN JETS

Having reviewed various mechanisms operating in a resonant screech loop, focus now shifts to practical applications involving screech. The twin-jet problem has

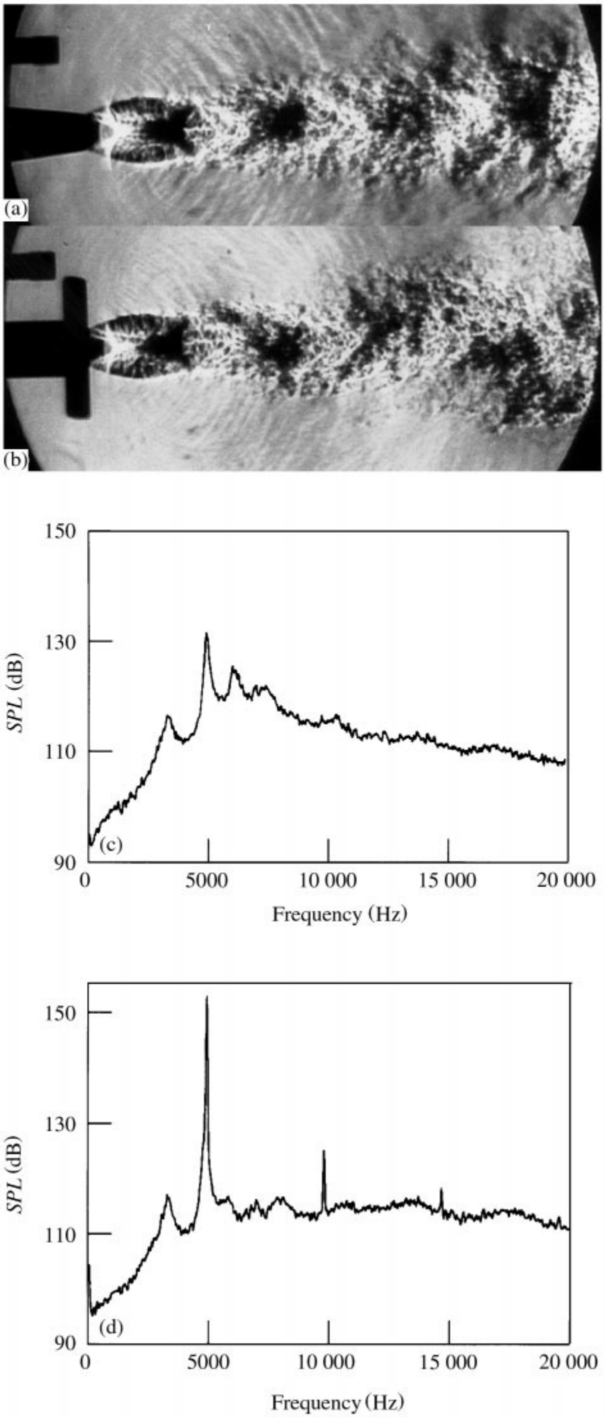


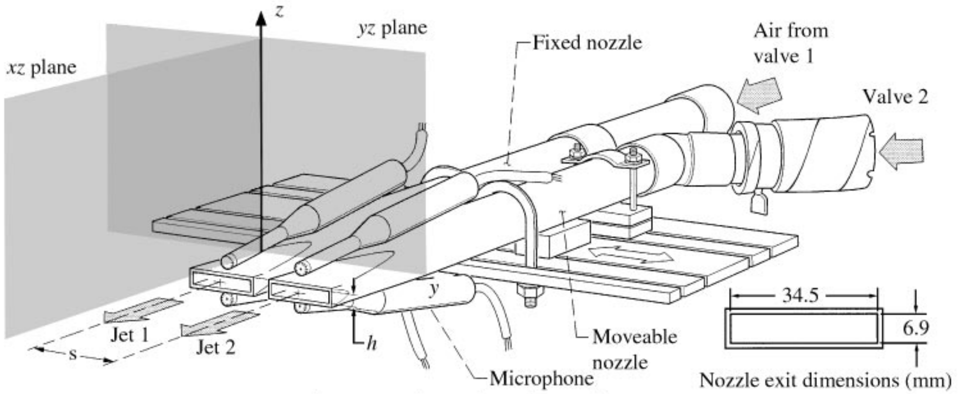
Figure 7. Spark schlieren photographs and spectra of screech reactivated by thickening the nozzle lip. $M_j = 1{\cdot}75$. (a,c) Thin lip, $t/h = 0{\cdot}2$. (b,d) Thick lip, $t/h = 2$. Spectra measured using a microphone located at $x = 0$, $y = 3{\cdot}7\ h$, $z = 0$ (adapted from Raman [92]).

received fresh emphasis due to concerns about modern aircraft. Coupling of twin jets from modern engines that are designed for very high propulsive thrust could produce very high dynamic pressures in the inter-nozzle region. In stealth applications, advanced materials (special paint or aircraft skin) could be damaged if the dynamic pressures are very large. In addition, complex nozzles on modern aircraft (e.g., the Lockheed F-22) have variable area and aspect ratios and thrust vectoring capabilities. The proper functioning of such a complex nozzle system with actuators under adverse conditions is of concern.

Considerable work has been done on twin-jet models to alleviate problems with the U.S. Air Force B1-B and F15-E — at the NASA Langley Research Center [37, 38, 43]; at the U.S. Air Force [82, 83]; and at McDonnell Douglas Aerospace [47, 48]. Coupled multi-jets in various configurations were also studied by Umeda and Ishii [120]. Recent work by Raman and Taghavi [95] focuses on fundamental mechanisms by assessing the steady and unsteady aspects of twin jet coupling. Two rectangular nozzles are placed side-by-side, with their narrow dimensions parallel and their long dimensions in the same plane. A positioning apparatus keeps one of the nozzles fixed and moves the second to achieve various internozzle spacings. Microphones on the nozzles monitor acoustic field characteristics, and a movable microphone measures the acoustic phase and amplitude distribution on the xz and yz planes. The sound pressure amplitude distributions on the y–z plane are shown in Figure 8 for two slightly different jet Mach numbers. The slight difference in operating conditions caused completely different modes of jet coupling. Mode I (antisymmetric) coupling minimized the sound pressure levels in the inter-nozzle region whereas mode II coupling augmented it. The Raman and Taghavi [95] paper also provides a plausible explanation for how the jets choose a coupling mode and documents mode transition.

6.2. SCREECH FROM NOZZLES OF NONUNIFORM EXIT GEOMETRY

Interest in non-uniform jet exit geometries dates back to the early developmental stages of the Concorde [134–137]. During noise reduction attempts with the Concorde, the Olympus engines were fitted with innovative variable-geometry intake and exhaust nozzle assemblies. The variable exhaust nozzle (Clamshell) could either close completely to reverse engine thrust or be only slightly closed to form a notch, thus squeezing the jet and altering the exit geometry. Note that apart from nozzle exit modification, nozzle inlet geometry [138] and the presence of swirl [139] are factors that affect screech. In recent years, several researchers have manipulated the internal contour of jet nozzles cleverly for thrust vectoring, enhanced mixing, and noise reduction. In the published literature such nozzles have been referred to by various names as “asymmetric” [40, 46, 119, 140], “scarfed” [141], and “bevelled” [99, 100, 102]. Further, rectangular nozzles with non-uniform exits are currently used on advanced military aircraft because of their unique stealth and thrust-vectoring capabilities. However, despite their benefits, such altered nozzles could screech differently, a concern that was recently addressed by Raman [93].



Twin supersonic nozzles and co-ordinates

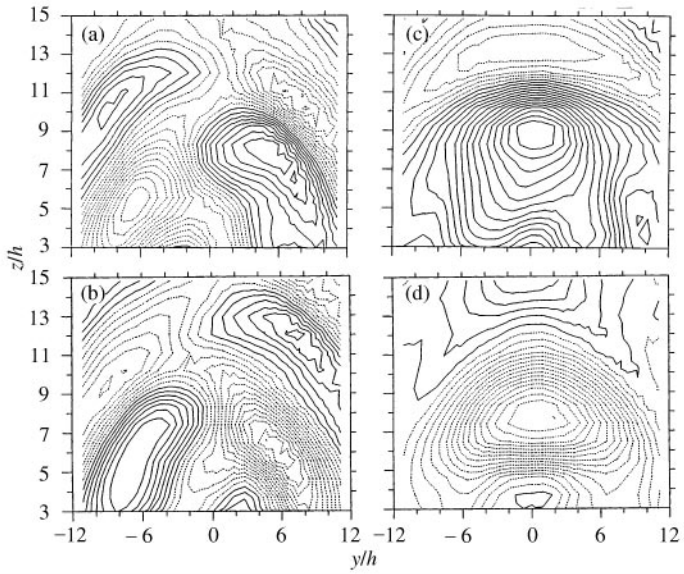


Figure 8. Phase-averaged near acoustic field in the *yz* plane for twin jets coupled in mode I (a,b) and mode II (c,d) (from Raman and Taghavi [95]). For each nozzle two phases of the screech cycle that are 180° apart are shown. Note that the solid and dashed lines represent positive and negative phases of the screech cycle, respectively. Sketch showing twin-nozzle set-up and co-ordinates appears above.

For the three nozzles used in Raman's [93, 96] work [(A) uniform, (B) single bevelled, and (C) double bevelled] three types of spanwise modes are possible: (I) symmetric, (II) antisymmetric, and (III A,B) oblique. The type of mode depends on the spanwise shock-cell structure. Note that all screech modes are antisymmetric in the transverse (y) direction. Spark-schlieren photographs for a convergent nozzle with a uniform exit and for the three nozzles under consideration are shown in Figure 9 side-by-side with instantaneous pressure maps on the *xz* plane. These photographs reveal the spanwise shock-cell structure and are useful in conjunction with the instantaneous pressure maps—to help us understand mode transitions and their dependence on the spanwise shock-cell structure. The screech frequencies produced by the nozzles of complex geometry (shown in Figure 10) could be

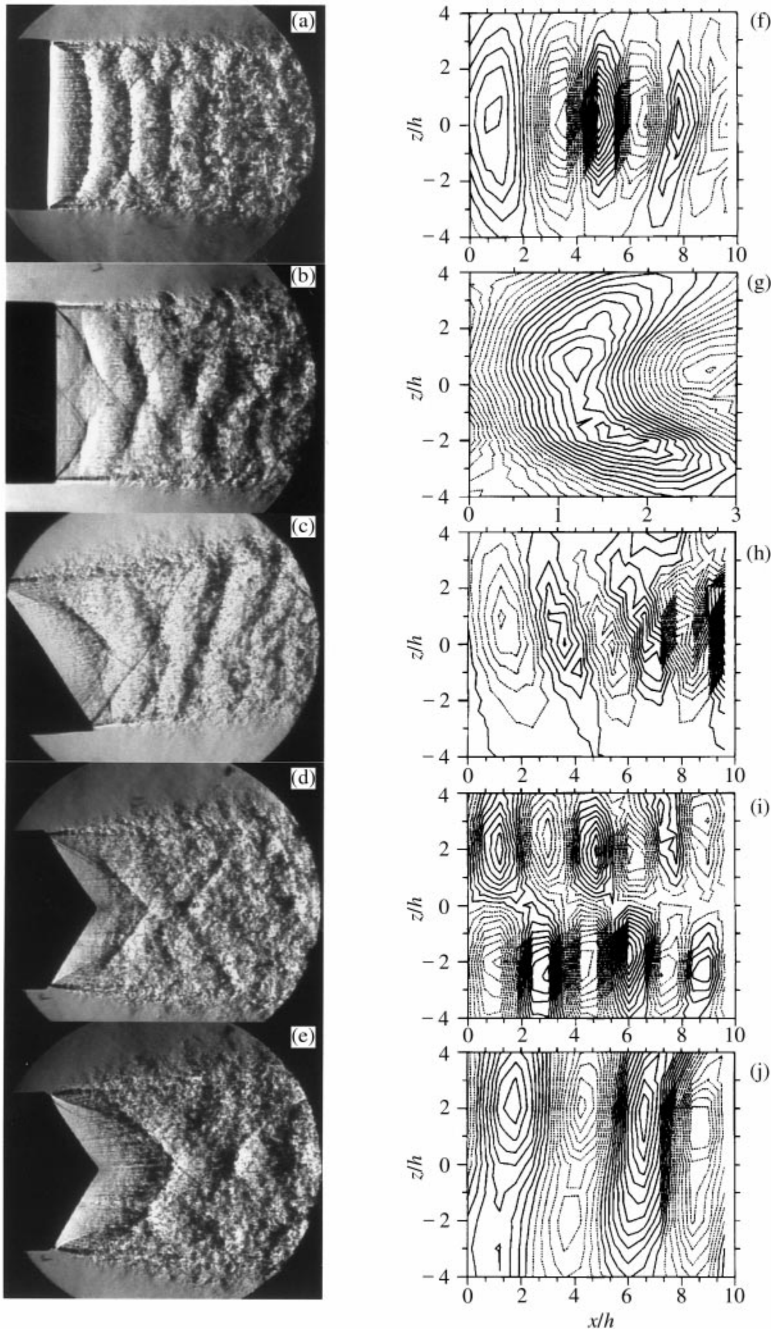


Figure 9. Spark schlieren photographs of the spanwise view and phase-locked pressure distributions on the spanwise (xz) plane for jets from nozzles of complex geometry (adapted from Raman [96]). (a–e) Schlieren photographs. (f–j) Pressure distribution. (a,f) Convergent nozzle with a uniform exit, $M_j = 1\cdot5$. (b,g) Convergent– divergent nozzle with a uniform exit. $M_j = 1\cdot26$, $M_d = 1\cdot4$. (c,h) Convergent–divergent single bevelled nozzle, $M_j = 1\cdot5$, $M_d = 1\cdot4$. (d,i) Convergent–divergent double bevelled nozzle, $M_j = 1\cdot5$, $M_d = 1\cdot4$. (e,j) Convergent–divergent double bevelled nozzle, $M_j = 1\cdot7$, $M_d = 1\cdot4$. In parts (f–j) solid and dashed lines represent positive and negative phases of the screech cycle, respectively.

calculated using a waveguide approach [75]. The waveguide approach also makes it possible to have several feedback loops and more than one screech tone at a given time. The major difference between screech from uniform and non-uniform nozzles is that the dominant waveguide modes that make up the quasiperiodic shock-cell structure are not necessarily the lowest order modes.

6.3. USING SCREECH TO ENHANCE JET MIXING

It is well known that artificially exciting a flow within a band where the jet is naturally sensitive can enhance mixing [56, 60, 86, 87, 142]. Since the growth of the natural jet instability produces screech, most likely this tone's feedback will excite the jet strongly and possibly produce enhanced jet mixing. Researchers familiar with screech during the early days noted that a screeching jet had the appearance of a "disintegrated" jet [143]. Hammitt [144] found that sound waves can interact with the jet and affect the jet's shock-cell structure. The first systematic study of the effect of screech on the mean jet velocity decay was performed by Glass [145]. He found that the axial velocity without feedback can sometimes be 50–100% greater than that with feedback, all other conditions being the same. From the data of Glass [145], it appears that mixing enhancement depends on the nozzle pressure ratio, which determines the frequency, amplitude, and mode of screech for a circular jet. Changes in mixing enhancement with Mach number are not influenced so much by the expansion/compression waves as they are by the presence or absence of screech. The dramatic effect on the mixing produced by the screech feedback loop indicates that there is a tremendous potential for enhancing mixing in compressible flows (that have inherently lower spreading) if we introduce appropriate active feedback control.

In cases where screech does not occur naturally it can be induced for purposes of mixing enhancement and noise suppression [101, 102]. The induced screech concept is based on a class of tones created by flow impinging on obstacles. In the past, such tones have been referred to broadly as edgetones [77, 146–148] or impingement tones (see Henderson and Powell [149, 150]). Krothapalli *et al.* [77] used edgetones for enhancing mixing in an array of subsonic jets. Rice and Raman [99, 101], Rice [102], and Raman and Rice [90] demonstrated the use of a supersonic edgetone for jet mixing enhancement. This technique was applied by first operating a rectangular convergent–divergent nozzle at its design Mach number (to minimize natural screech) and then inserting square obstacles on either side of the narrow dimension to set up a resonant oscillation. At downstream locations, a mass flux enhancement of about 30% was obtained. However, the obstacles caused a thrust penalty of almost 20% of the jet's ideal thrust. Raman and Rice [90] demonstrated that by proper shaping of the obstacles the thrust penalty can be reduced significantly.

One should note that if the jet impinges on an obstacle that is a tube open at one end then the resulting phenomenon is entirely different from that described above. When an underexpanded jet is directed towards the open end of a tube that is closed at the other end the arrangement is referred to either as the Hartmann whistle or the Hartmann–Sprenger tube, depending on the length of the tube [151, 152]. In the former case, a tone is produced with a slight temperature rise, whereas in the latter case a violent oscillation of the air column in the tube occurs and very high temperature is produced at the closed end. For details of this very interesting problem the reader is referred to Iwamoto [151, 152].

7. COMPUTER SIMULATIONS OF SCREECH

In recent years there have been several numerical studies of various aspects of screech and induced screech. An effort called Fluid Mechanics of Screech Program (FLUMES) was initiated by the U.S. Air Force to study the physics of the screech phenomenon and to build a tool that could predict screech sound pressure levels for the nozzle designer. Scientists at McDonnell Douglas Aerospace (now Boeing, St. Louis) developed a modular approach that included all physical elements of the resonant screech loop. Their work is described in a series of papers [49, 54]. They calculate instability wave growth assuming hyperbolic tangent velocity and temperature profiles for the mean flow. Next they calculate the sound produced by the instability–shock interaction using the analytical model of Kerschen and Cain [153]. Further, they obtain feedback of sound to the nozzle exit based on the cylindrical farfield decay approximation. Finally, they model the nozzle lip receptivity using a Wiener–Hopf analysis [54]. The McDonnell Douglas model results compared favorably with experimental data taken at the NASA Lewis Research Center [89].

Simulations of induced screech were conducted by the group at the Naval Research Lab (NRL) [121–123]. They solved the unsteady three-dimensional Euler equations using a flux-corrected transport (FCT) algorithm and used a virtual cell embedding (VCE) method to resolve complex geometries on a structured orthogonal grid. They successfully simulated the frequency, amplitude and thrust loss for conditions that corresponded to the NASA Lewis experiments [101, 90].

Recent attempts to simulate screech include the work of Manning and Lele [125] and Tam and Shen [76]. The former simulated an isolated weak jet screech source by replacing the shock-containing jet with a forced supersonic shear layer and impinging upon it a single oblique, near isentropic compression wave. They found the waveform of the radiated acoustic field to be comprised of a short compression followed by a longer expansion; its amplitude was linearly dependent on the imposed compression pressure wave rise. The latter successfully simulated the axisymmetric modes that occur at a low supersonic jet Mach number in circular jets using the dispersion relation preserving (DRP) scheme with artificial selective damping and appropriate boundary conditions. In the future, we can expect to see the extension of such simulations to time resolved three-dimensional calculations leading the way for screech amplitude predictions.

8. CONCLUSIONS

This brief review traced our progress in understanding the fascinating subject of jet screech from Powell to the present. It is clear that Powell's theoretical ideas have not only passed the test of time but have provided insight for a variety of related problems. Advances in experimental diagnostics and computational techniques have enhanced our knowledge of various aspects of screech. Although we have been able to calculate the growth of instability waves in supersonic flows and model instability–shock interactions, we still do not have a screech amplitude prediction model. It appears that the key to this lies in understanding feedback and receptivity. They are clearly important because although similar processes (with the exception of feedback to the nozzle lip) produce screech and broadband shock noise, we can predict the amplitude of the latter but predicting the former remains an elusive goal. Screech also illustrates the immense potential for using a self-sustained feedback loop to enhance mixing in compressible flows (at high convective Mach numbers) that inherently spread at lower rates. It is hoped that in addition to being a resource this review will arouse even more interest in this challenging subject.

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