# Interactions between Screech Tones and Ejector Performance

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**The thrust augmentation and the dominant acoustic frequency of a family of simple ejectors have been measured at primary stagnation pressures up to 6 atm. The convergent primary nozzle induced atmospheric air into a selection of constant diameter ducts that provided length-diameter ratios between 1 and 11 and an inlet area ratio around 25. The thrust-augmentation data tended to follow the monotonic reduction in performance that theory predicts with increasing pressures, except at certain pressures where the trend reversed. At these pressures, the acoustic frequency tuned to a transverse resonant mode of the mixing duct. It is speculated that resonance intensifies the large-scale vortices that mix the two streams and, at the same time, give rise to screech tones by interacting with the shock structure in the underexpanded jet.**

## Nomenclature

| | |
|---|---|
| $A_0$, $A_1$ | = area of primary, secondary streams |
| $C_F$ | = skin friction coefficient |
| $C_F^*$ | $= C_F(V_{\text{wall}}/V_2)^2$, augmented friction coefficient |
| $d$ | = diameter of convergent primary nozzle exit |
| $d_o$ | = 1 in., diameter of reference nozzle |
| $D$ | = diameter of mixing duct |
| d$a$ | = elemental area |
| $F$, $F_N$ | = thrust of ejector, nozzle |
| $F_{\text{isen}}$ | = thrust obtained by isentropically expanding the measured primary mass flow from reservoir to ambient pressures |
| $f$ | = frequency of screech tones |
| $f_S$ | $= f(d/d_o)$, frequency scaled to the screech from a 1-in.-diam jet |
| $L$ | = length of ejector from primary injection plane (throat of bellmouth) to exhaust plane |
| $m_{\text{actual}}$ | = measured primary mass flux |
| $p_1$ | = static pressure at the plane of injection |
| $P_{\text{res}}$, $P_A$ | = total pressure in the primary reservoir, ambient |
| $r$ | = radial distance from the ejector's axis of symmetry |
| $u$ | = local speed of flow |
| $v$ | = radial acoustic perturbation velocity |
| $V$ | = mass averaged velocity |
| $V_{\text{isen}}$ | = velocity obtained from isentropically expanding from reservoir to ambient pressures |
| $V_{\text{wall}}$ | = velocity at outer edge of boundary layer |
| $V_2$ | = mass averaged velocity of mixed flow |
| $\beta$ | $= \int (\rho/\bar{\rho})\ (u/V)^2\ \mathrm{d}(a/A) \geq 1$, the skewness factor |
| $\xi_F$ | $= 2C_F(L/D)\ (V_{\text{wall}}/V_2)^2$, the friction factor |
| $\eta_N$ | $= F_N/F_{\text{isen}}$, nozzle thrust efficiency |
| $\rho$, $\bar{\rho}$ | = local, mean density of flow |
| $\varphi$ | $= F/F_{\text{isen}}$, thrust augmentation ratio |

## Introduction

EARLIER experiments[1] using air expelled from a convergent nozzle into constant-area cylindrical ejectors produced unexpected trends associated with discernable changes in radiated noise. Theoretical calculations prescribed a monotonic decrease in performance with increasing primary pressure ratio and this trend was, in fact, observed in data obtained with long mixing ducts. The anomalies developed as the lengths of the ejectors dropped below 6 diam. Graphs of the mass-entrainment performance obtained with the shorter configurations gave the general impression of two relative maxima superimposed on a curve of inverse dependence on the pressure ratio. Typical data that contrast the performance of long and short ejectors are presented in Fig. 1. Theory stressed that the peaks of the relative maxima could only have been achieved if mixing between the primary and entrained streams had been completed, or nearly so. Velocity profiles measured in the ejectors' exhaust planes confirmed the well-mixed condition of the flow when the relative maxima occurred.

As the length of the ejector was reduced and testing proceeded, it became apparent to all within the laboratory that the quality of the sound radiated by the ejectors changed, often abruptly, as pressures increased throughout the test range, 0 to 80 psig. Along with the "rushing" sound characteristic of fluids in motion, the aural sensation of discrete tones persisted over repeatable pressure intervals.

Performance maxima were soon qualitatively tied to shifts in the dominant tones, thereby suggesting that an acoustic interaction had accelerated the rate of mixing and increased performance. Prior work[2-5] had identified the susceptibility of turbulent jets to deformation by acoustic signals, and Powell's[6] pioneering effort had established the candidacy of

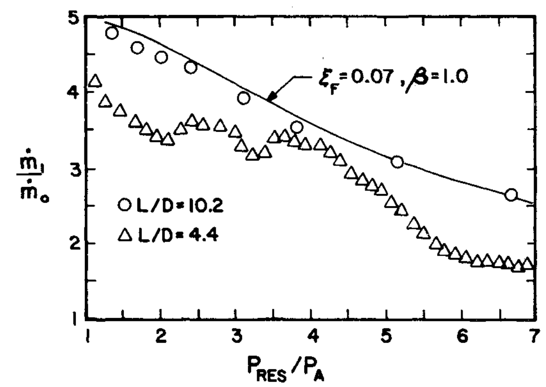


**Fig. 1 Typical mass entrainment performance characteristics for long ($L/D = 10.18$) and short ($L/D = 4.36$) ejectors. Solid line computed from the theory discussed in Ref. 1.**

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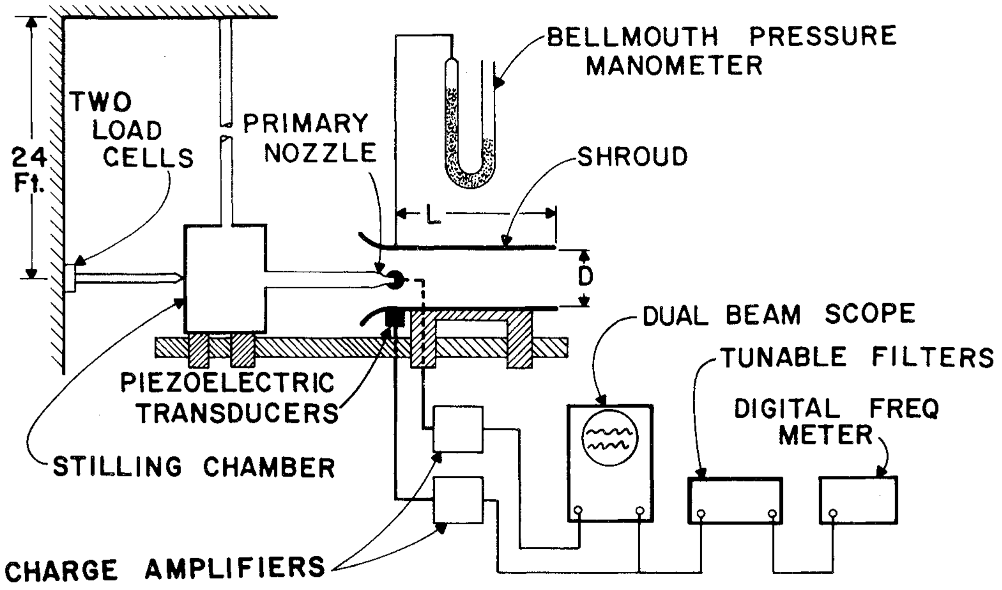


**Fig. 2 Schematic diagram of experiment and apparatus.**

screech or shock noise in the underexpanded primary jet as the origin of the deforming signal. That screech persists in shrouded, underexpanded jets had been previously confirmed[7-11] by efforts that examined the acoustic properties of ejectors. Noise suppression was the principle motivation behind these studies, and, without exception, the possibility of interactions between noise and performance received no mention. On the other hand, in a paper concerned with performance, Reid[12] described abrupt, irregular changes in secondary flow speed in an ejector that produced intense, discrete frequency noise. In the absence of any noise measurements, he casually ascribed the discrete frequency noise to "organ pipe" resonance dependent on shroud length. In contrast, the pumping performance of the ejectors tested in Ref. 1 maximized at pressure ratios that were independent of length.

The present work takes a closer look at the acoustic interaction and describes its effect on the thrust augmentation performance of a family of ejectors.

## Equipment and Procedure

The general arrangement of the laboratory equipment appears in the schematic diagram of Fig. 2. The shroud of the ejector consisted of an aluminum bellmouth inlet that mated smoothly to a family of eleven cylindrical, $D = 1.375$-in.-i. d. stainless steel tubes whose lengths varied from 15.4 to 1.7 in. Another 10-in.-long × 0.5-in.-i. d. stainless steel tube directed the primary air flow from a reservoir to a $d = 0.265$-in. convergent nozzle whose exit plane included the throat of the bellmouth. Most of this hardware had been used in the previously mentioned mass augmentation experiments. In the present tests, the primary nozzle was fed from a large (16 in. diam × 18 in. length) stilling chamber that comprised the mass of a constrained pendulum balance. The facility, used extensively[13] in the past to measure two components of force, was ideally suited to measuring the thrust of small ejectors. Shrouds were attached through a "slot and bolt" alignment device to a Unistrut assembly that bolted to the base of the stilling chamber.

Forces were measured by two coplanar Statham Model UC 3-UL4 strain-gage load cells, whose signals were amplified with Daytonic Model 601B Signal Conditioners and recorded on Hewlett Packard Model 2FA X-Y-Y recorders. The entire system was calibrated with standard weights prior to each run. Primary mass flow rates were measured with a precalibrated venturi meter, permanently installed in the supply line.

In obtaining performance data, the pressure in the stilling chamber was increased in approximately 2-psi increments across the range $0 \leq (P_{res} - P_A) \leq 70$ psig. At each test point, load cell readings, reservoir conditions, mass flow data, and, occasionally, bellmouth pressure, were recorded and reduced to form the thrust augmentation ratio $\phi = F/F_{isen} = F/(\dot{m}_{actual} V_{isen})$. Measurements were also taken at decreasing pressure increments. After the results had been examined, the mixing duct was shortened and the above procedure repeated. There eventually resulted a good description of the effect of length on the thrust augmentation performance of an inlet area ratio $A_1/A_0 = 25.8$ ejector. One test was run without a shroud, the above procedure leading to the thrust efficiency of the nozzle $\eta_N = F_N/F_{isen}$.

Three holes, spaced at 90-deg circumferential intervals, in the primary injection plane, were drilled through the wall of the bellmouth to accommodate two fast-response, crystal pressure transducers. These were Kistler Model 603A devices with a 0.23-in. diam and were used to measure frequency and circumferential phase relationships in the unsteady or acoustic pressures excited within the ejector. The manufacturer had quoted 3$\mu$sec characteristic response times, an order of magnitude faster than was required. Signals from the transducers were conditioned with Kistler Model 504F dual mode charge amplifiers and then displayed on a Tectronix Model 555 dual beam oscilloscope. By collocating the pressure transducers and simultaneously submitting them to the screech tone of a jet, it became clear that the circuitry provoked no changes in the relative phases of the signals.

The strongest component, or fundamental, of the frequency of the screech tone was estimated easily by noting the sweep speed of the oscilloscope and the trace period. A more precise determination was obtained by branching one signal through an SKL Model 302 Variable Electronic Filter to a General Radio Model 1192 electronic counter set to display frequency. This arrangement can also be seen in Fig. 2. The filter was used in a band pass mode set at the estimated frequency ±20 kHz, approximately. The bandwidth was arbitrarily determined, but an addition of ±5 kHz usually produced a change of less than a few kHz in the displayed frequency.

The first series of noise tests were conducted without the ejector's shroud. This information served two purposes: it identified the idiosyncrasies of the present nozzle's screech characteristics and, also, together with the large body of data in the literature, it provided an assessment of the experimental technique and procedure. A special jig was made to position the transducers approximately 1 in. from the centerline of the nozzle, in the plane containing the nozzle's aperture and circumferentially separated by either 90 or 180 deg. Frequency and phase relationships were manually recorded as the reservoir pressure was increased from 0 to 60 psig, usually in 1 psi increments. Reservoir temperatures remained around 65°F, approximately 5°F below ambient. As the frequencies passed through the discontinuous jumps that characterize screech tones, the pressure increment was reduced from 1 to 0.1 or 0.2 psi. Photographs were frequently taken of the oscilloscope traces, usually at 5 psi increments.

The bare nozzle tests were repeated several times with the transducers at both the 90 and 180-deg circumferential positions. In some instances, hard surfaces like the nozzle tube, the transducers, and the reservoir were wrapped with a sound absorbing material. A second set of tests was made with the nozzle discharging into a 2 ft×2 ft×3 ft long "anechoic chamber," whose downstream wall had been partially cut open to allow the jet to escape. The data from the two bare nozzle tests agreed perfectly and suggested that correct screech frequencies devoid of the effects of spurious reflections had been measured.

## Results

The performance of the 11 ejector configurations, in terms of the dependence of thrust augmentation ratio on primary pressure ratio, has been presented in Figs. 3 and 4. The latter also includes data obtained with no shroud at all and should be labeled, more properly, the nozzle thrust efficiency, rather than the thrust-augmentation ratio.

The data bear scant resemblance to the monotonic reduction in performance that theory predicts for increasing pressure ratios. Erratic trends prompted the repetition of most experiments, which served only to substantiate the original data. Further confirmation of the reality of the data derived from the apparent similarity in the data obtained with

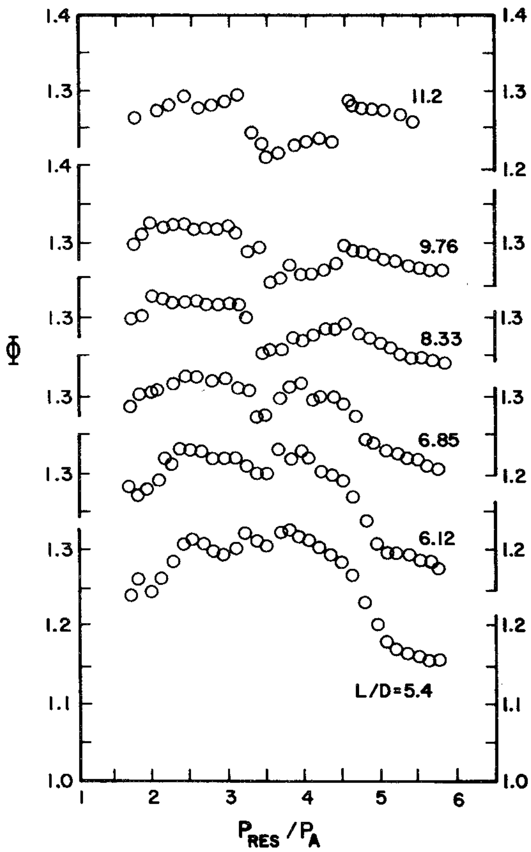


Fig. 3 Ejector performance, thrust augmentation ratio against pressure ratio $11.2 \geq L/D \geq 5.4$.

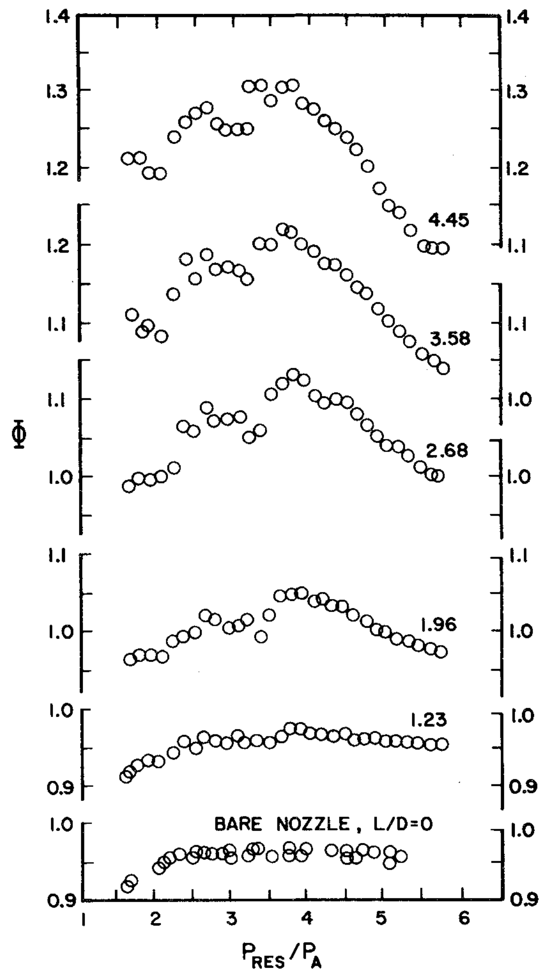


Fig. 4 Ejector performance, thrust-augmentation ratio against pressure ratio $4.45 \geq L/D \geq 0$.

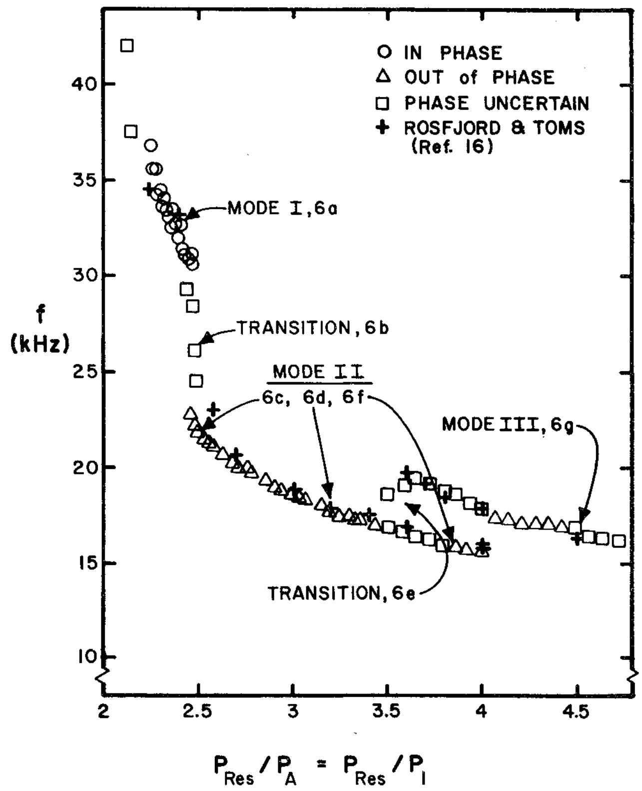


Fig. 5 Dependence of the bare nozzle's screech frequency on pressure ratio. Corresponding oscilloscope traces in Fig. 6 are indicated by the arrows.

different configurations. A sharp reduction in performance occurred over the approximate interval $3.2 \leq P_{res}/P_A \leq 4.5$ with the $L/D = 11.2$, 9.76, and 8.33 ejectors. The remainder exhibit relative maxima around $P_{res}/P_A \approx 2.7$ and 3.7, a result which had been anticipated from the earlier work.[1]

The effect of pressure ratio on the screech frequency of the bare nozzle can be seen in Fig. 5. Data obtained by Rosfjord and Toms[14] using the present nozzle, but employing an entirely different experimental technique, have also been plotted. Little, if any, difference in the two sets of measurements is apparent. In addition, if one follows a suggestion of Middleton[11] and plots a frequency $f_S = f(d/d_o)$, scaled to a nozzle diameter of $d_o = 1$ in., there results a pattern consistent with most previous investigations.

Screech tones from the bare nozzle were observed soon after the pressure exceeded the choking or critical value. Frequencies were first measured at a pressure ratio slightly higher than 2.1 and decreased rapidly with increasing pressure. In the range $2.2 \leq P_{res}/p_1 \leq 2.45$, called Mode I, the tones derive from symmetric disturbances in the jet[15-17] and signals from microphones positioned at an interval of 90 or 180 deg around the jet are in phase (Fig. 6a). At a pressure ratio of 2.45, approximately, the disturbances quickly transition to a second mode. Frequencies were measured during the transition but the waveforms, which were M-shaped in the mean (Fig. 6b), failed to provide reliable phase information. This problem was resolved once the disturbance had been firmly established as Mode II. Figure 6c and 6d and, less clearly, Fig. 6f support prior observations[6,15-17] that disturbances in the jet during Mode II are nonsymmetric and produce out-of-phase screech tones. A transition to a third mode, quite distinct from the rapid transition first encountered, occurs across the pressure range $3.4 \leq P_{res}/P_1 \leq 4.1$. During transition to the third mode, complicated oscilloscope traces (Fig. 6e) usually failed to provide phase information. Frequency was also difficult to estimate from the traces, although there were occasional moments (Fig. 6f) when both phase and frequency could be delineated. The aural sensation provided by the jet's noise during transition suggested a multiplicity of tones superimposed on a very loud "rushing" sound. However, only two sets of frequencies were identifiable from the traces during transition and, as mentioned above, these were sporadic. More precise measurements of the pair of tones were achieved by selectively narrowing the width of the band passed by the filter system. The signals encountered in Mode III tended to support the previous[15-17] association of these screech tones with asymmetric disturbances. On the whole, oscilloscope traces obtained in Mode III (Fig. 6g) were far less clear than their counterparts in Mode II, and degraded further with increasing pressure. Finally, at pressure ratios just greater than five, our instruments and our hearing no longer detected clear screech tones.

The single sweep traces of Fig. 6 clearly carry a very high-frequency signal, approximately 150 kHz. Because it seemed to bear no relationship to the objective of this study, its source was not investigated. One cannot discount the possibility that the high-frequency component was a product of the instrumentation, although Powell,[6] Westley and Woolley,[17] and others have also noted its presence. The phenomenon, if real, appears to have escaped serious study.

In Fig. 7 have been plotted the frequency and thrust augmentation characteristics of the $L/D = 5.1$ ejector. The abcissa $P_{res}/p_1$ is the pressure ratio referred to injection

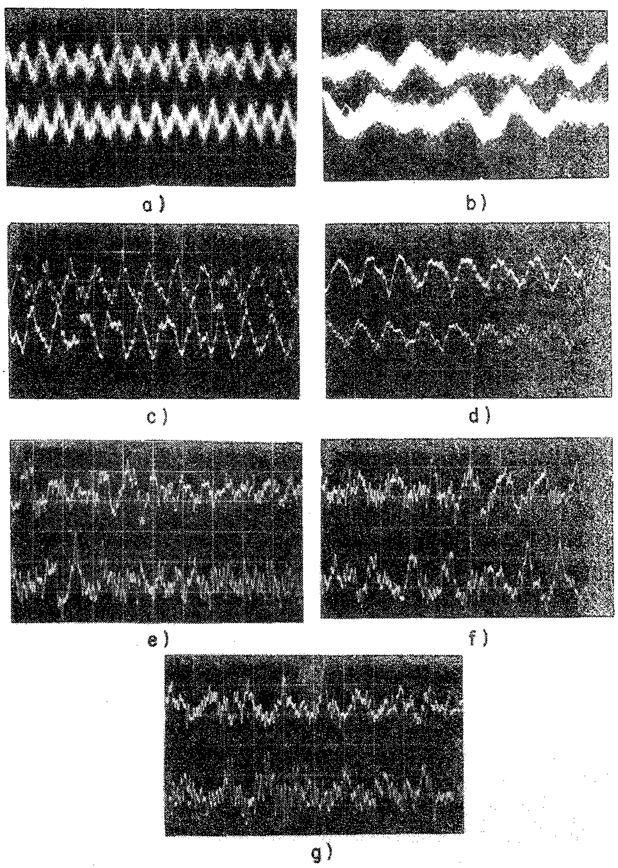


Fig. 6 Oscilloscope traces of the signals sensed by two transducers on opposite sides of a free jet at various pressure ratios. 50 $\mu$sec/cm sweep speeds. $P_{res}/p_1 =$: a) 2.4, b) 2.49, c) 2.52, d) 3.15, e) 3.62, f) 3.87, g) 4.46.

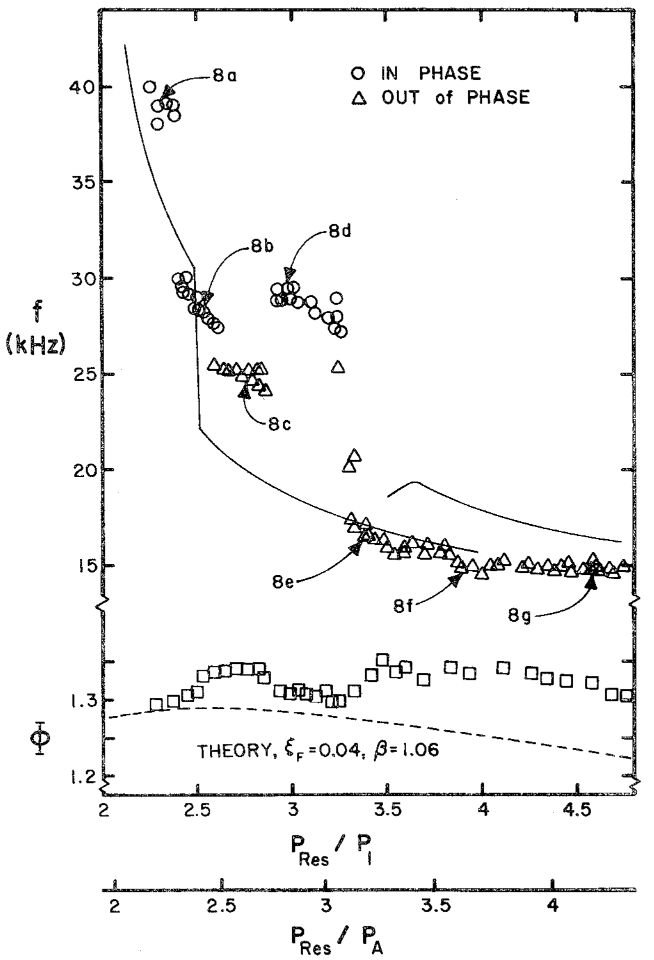


Fig. 7 Dependence of the $L/D = 5.1$ ejector's screech frequency and thrust augmentation ratio on the pressure ratio referred to inlet conditions. Corresponding oscilloscope traces in Fig. 8 are indicated by the arrows. Solid lines describe free jet data.

plane, rather than ambient, conditions. This choice was prompted by previous investigations which firmly established the relationship between screech tones and the shock structure of underexpanded jets. Since the latter depends on nozzle pressure relative to its environmental pressure, and since it was desired to contrast bare nozzle and ejector screech characteristics, the choice of $P_{res}/p_1$ seemed more appropriate than $P_{res}/P_A$. This departs from the precedent set by Middleton,[11] who chose to present his acoustic data for consistency with performance data obtained by Reid.[12] The scale appended below the abcissa of Fig. 7 indicates the difference between the two pressure ratios for the $L/D=5.1$ configuration. It is not too different for other configurations.

The lines drawn in Fig. 7 are representative of the data obtained with the bare nozzle. Similarities and differences between the screech characteristic of the bare and shrouded nozzle are evident. Of the four abrupt jumps in frequency that occur in the shrouded case, those in the interval $2.5 \leq P_{res}/p_1 \leq 3.5$ are most interesting, for they relate to shifts between symmetric and asymmetric disturbances. These are quite clear, more so than in the free jet case, in the oscilloscope traces shown in Fig. 8. The groups of data clustered around the points corresponding to 8a and 8b in Fig. 7 are in phase and probably relate to the free jet's Mode I, modified to some extent by the pressure of the shroud. Similar comments might be appropriate for the data clustered around 8e, where the signals are quite strong and reduced in harmonic content. The strongest signals were first measured near a pressure ratio of 3.9 and persisted a bit beyond 4.7. Thereafter, screech tones from the ejector followed the trend set by the bare nozzle and quickly disappeared altogether.

Screech frequencies from the ejector discussed by Middleton[11] also included a number of discontinuities, but no mention was made of phase relationships. In contrast to the rather flat regions described by much of the data in Fig. 7, all of Middleton's data slope downward to the right. This observation suggests that the discontinuities may have been provoked by factors peculiar to the experiments.

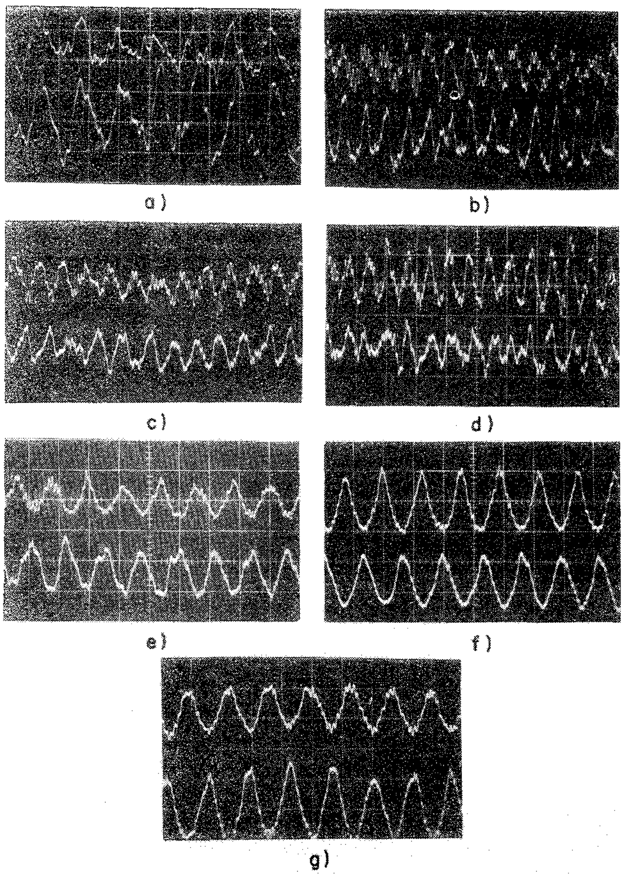


Fig. 8 Oscilloscope traces of the signals sensed by two transducers diametrically opposed and imbedded in the walls of an ejector's shroud. 50 $\mu$sec/cm sweep except for a) which is 20 $\mu$sec/cm.

## Discussion of Results

The Appendix of Ref. 1 describes an analytic procedure for computing the performance of ejectors. The effects of inlet and nozzle efficiencies, skin friction, and incomplete mixing are considered and treated parametrically, or functionally if their dependence on pressure ratio, or a related variable, is known beforehand. The thrust-efficiency data shown at the bottom of Fig. 4 provide information of the latter kind. Similar data have been obtained for the efficiency of the bellmouth inlet-with-nozzle used in these tests. Their combined degradation of the performance of an ideal $A_1/A_0=25.8$ ejector is apparent in Fig. 9. The curve computed with measured inlet and nozzle losses peaks at a pressure ratio around 2.5 and reflects the approach of the nozzle efficiency to its asymptotic value shown in Fig. 4. This characteristic persists in the remaining curves, which describe the debilitating effects of friction and incomplete mixing. Both the friction factor $\xi_F$ and the flow-skewness ratio $\beta$ seriously degrade ejector performance. It should be noted $\beta=1.0$ corresponds to a uniform, fully mixed flow, and that $\beta=1.1$ corresponds to a very poorly mixed flow. In this regard, if one were to calculate the skewness $\beta_0$ of the initial "top hat" profile formed by an incompressible primary and secondary stream at the plane of injection in an $A_1/A_0=26$ ejector, one would find $\beta_0=1.387$. This is the maximum value of $\beta$ that could occur in such an ejector, and decaying from 1.387 to 1.1 represents poor mixing within a short duct.

That $\xi_F$ and $\beta$ are not true constants but depend, in fact, on pressure ratio, is implied in Fig. 9 by the departure of the $L/D=5.4$ and 9.76 data from the trends proposed by theory. The performance of the shorter ejector at first, and ultimately, follows a calculation undertaken with $\xi_F=0.035$ and $\beta=1.1$. Across the pressure range where screech tones were observed, $2 \leq P_{res}/P_A \leq 5$, approximately, measured thrust-augmentation ratios exceed the predictions of theory by a substantial margin. One thus infers that mixing was enhanced, or that friction was reduced, or that both of these effects occurred in this pressure range. Conversely, over much of the same range of pressures, the performance of the longer ejector fell below the theoretical curve. The inference is that mixing was retarded, that friction was increased, or that both effects occurred.

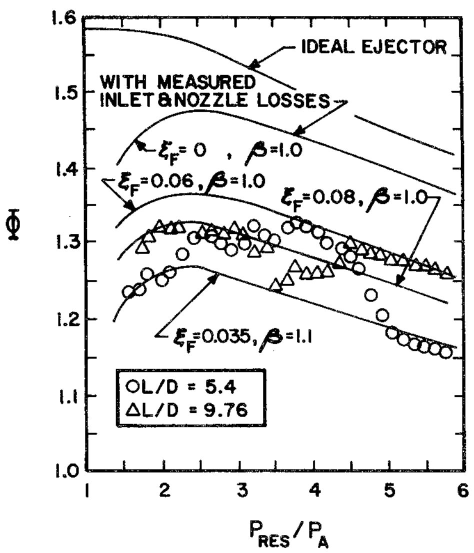


Fig. 9 Theoretical (solid lines computed according to the Appendix of Ref. 1) performance of an $A_1/A_0=25.8$ ejector contrasted with measured values.

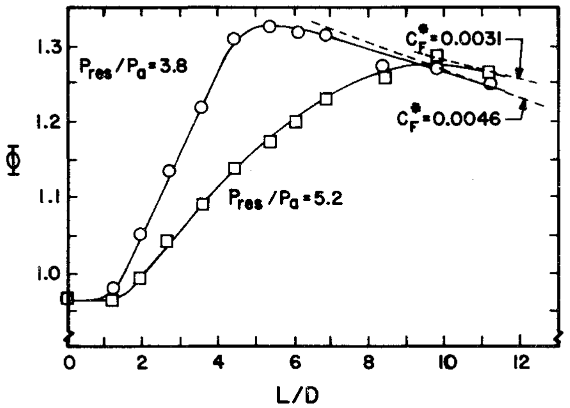


**Fig. 10 The dependence of thrust augmentation ratio on the length of the ejector. The broken lines are theoretical calculations that assume fully mixed flow ($\beta = 1.0$) and values shown for the augmented skin friction coefficients $C_F^*$.**

Which part, if any, of these variations in performance is due to changes in friction and which part to changes in mixing cannot be determined from Fig. 9, but it is important to recognize that friction and mixing are the only factors that could influence the performance of the geometrically simple ejectors used in these experiments.

Some feeling for the interplay between mixing and friction can be gleaned from Fig. 10, where the data of Fig 3 and 4, at $P_{res}/P_A = 3.8$ and 5.2, have been cross-plotted to show dependence on the ejector's length. Stretching the ejector at first improves its performance by providing the primary stream with a longer time to mix and transfer its energy to the entrained stream. Were it not for friction, the upward trend of the data would continue toward a flat asymptote representative of complete mixing. However, the reality of friction reduces performance in proportion to the ejector's length and causes the data to peak at $L/D$'s between 4.5 and 12, depending on the pressure ratio. The data actually asymptote the broken lines sketched in Fig. 10. These are the results of theoretical calculations that assumed fully mixed flows ($\beta = 1.0$) and values of the augmented skin friction coefficient $C_F^*$ printed on the figure. Larger values were required to match the data obtained at $P_{res}/P_A = 3.8$ than at 5.2. It is also apparent, from the relative slopes of the data, that mixing between the primary and entrained streams proceeded twice as rapidly at $P_{res}/P_A = 3.8$ than at 5.2. Choosing these pressure ratios to demonstrate trends in Fig. 10 was not accidental. At $P_{res}/P_A = 3.8$, screech tones are intense, almost pure tones (Fig. 8g). At $P_{res}/P_A = 5.2$, screech tones could not be detected. The data presented in Fig. 10, together with the rest of the data in Figs. 3 and 4, describe two deviations from expected performance that occur when screech tones occur: 1) the performance of short ejectors improves, and 2) the performance of long ejectors deteriorates. The remainder of this discussion offers a possible explanation for the interaction, implied by the data, between screech tones and performance.

The frequencies of the screech tones radiating from the ejector (Figs. 7 and 8) differ in several respects from the screech tone frequencies radiating from the free jet (Figs. 5 and 6). Abrupt jumps between more and different modes are more common in the ejector data which also appear not to develop the Mode II of Fig. 5. Part of the difference probably results from different aerodynamic conditions. While the free jet expands into a still environment, the ejector's primary jet expands into a severe pressure gradient surrounded by a coflowing stream. The clustering of data around particular frequencies suggests that resonance might also explain a significant part of the difference between the frequency characteristics of the free jet and those of the ejector.

Resonance of this sort has been observed before[10] and finding stronger coupling at the lower frequencies is more

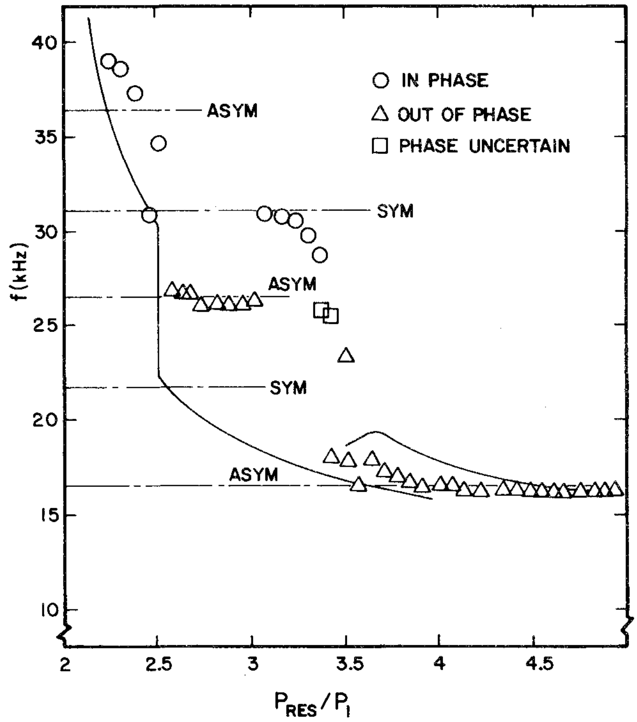


**Fig. 11 Frequency and phase characteristics of the $L/D = 5.1$ ejector operating with no secondary stream. Solid lines describe free jet data. Broken lines identify symmetric (SYM) and asymmetric (ASYM) resonant frequencies.**

common than not. Resonant frequencies of the duct were estimated by solving the simple wave equation, subject to finite perturbation amplitudes at $r = 0$, and $v = 0$ at $r = D/2$. An error in the latter boundary condition caused wrong resonant frequencies to be reported in the Note[20] that first discussed this work. The first four, correct, transverse resonant frequencies of the ejector shrouds used in these experiments are $f = 11.9$, 21.8, 31.6, and 41.3 kHz for the simplest symmetric modes and $f = 5.74$, 16.6, 26.5, and 36.3 kHz for the simplest asymmetric modes. In Fig. 7 the in-phase (symmetric) data cluster near 30 and 40 kHz and the out-of-phase (asymmetric) data cluster near 16 and 25 kHz.

Differences between measured and calculated frequencies were thought to relate to the inadequacy of the simple wave equation to describe the complicated events related to nonuniform flows through a duct. At the same time, it was recognized that the forcing function, the perturbations disturbing the underexpanded jet, was acting in an ill-defined environment consisting of a coflowing stream and a streamwise pressure gradient. An experiment was devised to see if better frequency agreement could be achieved in the absence of one of these factors, the coflowing stream.

The ejector was made to exhaust into a large plywood enclosure whose inside walls were covered with a sound-absorbing material. A valve regulated the flow out of the chamber, and, thus, the back pressure of the ejector. As the reservoir pressure was increased, the back pressure was adjusted until the bellmouth pressures rose to ambient, the condition of no entrained flow. Frequency and phase data obtained under these conditions are shown in Fig. 11 and reinforce the suggestion of coupling between disturbances in the jet and standing waves in the mixing duct.

Recognizing that screech tones tune to resonant modes of the mixing duct takes one a step closer in providing an explanation for the improved performance of short ejectors. Consider the corresponding sets of frequency and performance data presented in Fig. 7. At an inlet pressure ratio of $P_{res}/p_1 = 2.52$ performance abruptly jumps above a reasonable, theoretical trend line. Very shortly thereafter, at a pressure ratio of 2.56, the screech frequency jumps to an asymmetric resonance around 25 kHz. At $P_{res}/p_1 = 2.85$ both sets of data jump again; frequency is up corresponding to a symmetric mode around 30 kHz, and performance is down nearer to the theoretical trend line. This condition continues to a pressure ratio around 3.3, where frequency abruptly approaches asymmetric resonance near 16 kHz and performance jumps to another high level. The association of rapid changes in screech tones with equally rapid changes in performance underlies the hypothesis that acoustic signals interact with the heart of the ejector process, turbulent mixing. The mechanics of the interaction supposedly concerns large-scale vortex structures which experimentalists are crediting[18] with responsibility for entrainment in turbulent shear flows. In ejectors, these vortices are convected in the shear layers separating the primary and entrained streams. The rate at which vortices in the shear layer traverse the underexpanded jet's shock cells has been used by Powell[6] and others[15,16,19] to explain the origin of screech tones. The frequency of this activity therefore reflects the rate of entraining flow into the ejector. It thus becomes reasonable to associate the mixing rate with the mode and intensity of the screech tone. The impact of resonance is to fix the frequency of the vortices, to strengthen[21] them, and to intensify their ability to entrain fluid and promote rapid mixing. So it is that a short ejector, one whose performance suffers because insufficient length prevents complete mixing between primary and entrained streams, abruptly benefits from the onset of screech and resonance. The data in Fig. 7 suggest that more benefit derives from asymmetric modes than from symmetric modes.

Similar reasoning accounts for the loss in performance suffered by longer ejectors when they encounter asymmetric resonant modes. It is clear that the interactions discussed in the preceding paragraphs cannot improve the performance of long ejectors. These configurations provide ample opportunity for normal mixing processes to transfer the energy and momentum of the primary stream to the entrained flow. Accelerating the rate of mixing, by acoustic or other means, simply moves upstream the location at which a specific degree of mixing has been achieved. On the other hand, in describing the asymmetric disturbances of screech tones from free jets, Davies and Oldfield[15] and Westley and Woolley[17] observed pressure waves spiraling around the jet as they advanced downstream. It is known[22] that resonance involving spiral modes concentrates energy near the wall of a circular duct. The flow within an ejector accomplishes this through a distribution that places higher velocity fluid near the wall, as shown by the data of Fig. 9 in Ref. 1. In accelerating the mixing process, a resonant condition provides extended length along which relatively higher velocities provoke relatively larger friction losses. In Fig. 10, notice that theory described the trends of longer ejectors ($L/D \geq 9$) under resonant conditions ($P_{res}/P_A = 3.8$) only after increasing the augmented friction coefficient $C_F^* = C_F(V_{wall}/V_2)^2$ by 50%. Within the speculative context of acoustic interactions, performance data and velocity profiles suggest that resonance increases friction losses which, in turn, reduce the performance of long ejectors.

## Conclusions

The thrust augmentation produced by ejectors normally decreases with the primary pressure ratio and increases as their lengths approach seven to nine times their diameters. Further increasing length usually degrades performance proportionally. There are conditions, however, which reverse these trends. The measurements discussed in this article associated departures from expected performance with abrupt changes in the screech frequency radiated from the ejector. This suggested a hypothetical relationship between performance and screech tones, connected through the vortex activity within the shear layer of the primary jet. Resonance, at least those transverse modes that were observed, appears to intensify the vortices and accelerate the mixing process. Asymmetric resonant modes also concentrate kinetic energy near the walls of the mixing duct. The hypothesis accounts for both of the principal findings of this work: aeroacoustic interactions improve the performance of short ejectors and degrade the performance of long ejectors.

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