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Scaling of Fluctuating Pressures in Jet Impingement

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Scaling laws for the determination of fluctuating surface pressure loads on STOL aircraft due to jet impingement have been investigated using a quarter-scale model of a boilerplate test facility at NASA Langley, in which a JT-15D engine with a rectangular outer nozzle blows over a small curved airfoil representing the upper surface of a wing with flap extended. Whereas the full-scale engine has an internal hot core nozzle, there was no internal nozzle in the model, so that, not only was a condition of perfect mixing simulated, but also, this was done with a cold jet. It is known that the overall impingement pressures should be expressible in terms of five parameters, the pressure coefficient, the Strouhal number, the jet to ambient temperature ratio, the jet Mach number, and the jet Reynolds number. Comparing surface pressure spectra on the basis of the first two parameters, it is found that the model spectra peak at pressures which are 1.6 times the values indicated by the relevant scaling laws. This is tentatively attributed to the effect of the temperature ratio. Overall pressure coefficients are found to compare well, and to be independent of either temperature ratio, Mach number, or Reynolds number. It is concluded that a scaled cold jet run at low Reynolds and Mach numbers can be used to predict full-scale impingement pressures, although some uncertainty remains over the corrections for jet temperature effects, the corrections for different noncircular nozzle geometries, the effect of a separate core nozzle, and the effect of engine noise. These can only be resolved by suitable experimental programs.

I. Introduction

THE principal goal of this investigation has been to determine the scaling laws for the unsteady pressure loads on wing surfaces or flaps of STOL aircraft due to jet impingement. To achieve this goal, a quarter-scale model has been built of an existing boilerplate facility at NASA Langley. The full-scale facility uses a JT-15D engine with a rectangular fan nozzle and an internal elliptical core nozzle blowing over a small curved airfoil representing the upper surface of a wing and flap. The model is a cold flow facility which at present simulates the conditions of perfect mixing, there being no core nozzle. Not only has this model been used to study the nature of jet flows from rectangular nozzles, both in free flow and in an upper-surface blowing configuration, but also, direct comparisons have been made between unsteady pressure loads on the model and on the full-scale facility. In this paper, the authors present some results of the direct scaling investigation, and outline the development of the instrumentation used. A technique for scaling results from tests on small cold-jet models is presented in which the scaling parameters are the Strouhal number tentatively corrected for jet temperature and the pressure coefficient.

Considerable uncertainty exists over the validity of the suggested temperature correction to the Strouhal number. Since the quarter-scale model used a cold jet, requiring no correction, the problem of determining the true correction could not be addressed during the work reported in this paper. However, it is interesting to note that a somewhat similar form of correction has been used successfully to scale far-field noise spectra.

Some consideration has also been given to the problems of comparing different nozzle geometries, to the effects of internal core nozzles, and to engine noise. It is concluded that the modeling technique is capable of producing useful results, although several questions remain which could be cleared up by suitable experimental programs.

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II. Scale Laws for Jets

The scaling laws for fluid flow phenomena are, of course, well known, and it is clear that an adequate job of scaling a jet impingement configuration could be done if the correct Reynolds number and Mach number could be reproduced, if the internal noise spectrum of the engine were properly represented, and if the combustion products and temperatures were correctly modeled. Then the spectra of unsteady pressure coefficient power-spectral-densities, when plotted against Strouhal number, would be identical for both the model and for the full-scale system. Since it is virtually impossible to build a scale model meeting all of these requirements, one must consider to what extent these requirements can be relaxed, and to do this, one might look first at the jet structure itself for clues.

In reviewing the literature, one finds that the classical jet model, in which the sheared annulus is assumed to be turbulent, has been replaced by the vortex model, in which the apparent turbulence of the sheared annulus actually results from the passage of vortices, so that the flow is in fact highly structured. Early investigators, such as Powell,[1] Bradshaw et al.,[2] and Mollo-Christensen,[3] had suggested that the jet might be structured; while Davies,[4] Crow and Champagne,[5] and Lau et al.,[6] to name a few, contributed to the identification of the vortex structure; also Laufer et al.,[7] and Lau and Fisher[8] investigated the complex structure in more detail. Other authors reported on flow-visualization experiments, which tended to confirm the vortex model.

An item of particular interest is the discussion of Reynolds number effects by Crow and Champagne, who show that, once it exceeds 10^4, there is little significant effect upon the jet structure. Evidently, at such values, the viscosity dominated turbulence is overwhelmed by the large-scale action of the vortices. An important result of this effect is that it should be possible to eliminate the Reynolds number as a scaling parameter, and thus to simplify the design of models. Information on the subject of non-circular jet flows is almost nonexistent, but the authors[9] did present some results of flowfield studies in a rectangular jet.

Scaling Parameters for Impingement

The possible scaling parameters for the fluctuating pressures in near-field jet impingement are as follows: Strouhal number $St = fD_{eq}/U_j$, pressure coefficient $c_p = p/q_j$, jet temperature ratio $= T_j/T_a$, jet Mach number $M_j =$

U_j/c_j, and Reynolds number $R = \rho_j U_j D_{eq}/\mu_j$, where the subscripts j and a refer to properties of the jet and of the ambient air, respectively, f is the frequency, D_{eq} an effective diameter, not precisely defined for noncircular jets, U_j is the jet velocity, p is the static or surface pressure, q_j is the total head of the jet flow, T is a static temperature of the flow, c is the speed of sound, ρ is the density, and μ is the viscosity. If the coaxial jets are to be considered, or if engine noise is to be included, the preceding list could grow.

Restricting ourselves to simple circular jets fed from nonturbulent plenum chambers and ignoring the Reynolds number R we have four parameters. The most common relationship studied between these is the power-spectral-density of the free-flow or static pressure coefficient c_p expressed as a function of the dimensionless frequency St, the Strouhal number. This is generally seen to peak at a Strouhal number of about 0.3, but after about five jet diameters (D_j equals D_{eq} for circular jets) downstream, the peaks begin to disappear and the spectrum becomes typical of normal turbulence. Similar spectra are noted for surface pressures due to jet impingement. The spectral peaks in the first five diameters are apparently related to the passage of vortices, often referred to as constituting the large-scale jet structure.

Scaling Parameters for Far-Field Noise

A comprehensive discussion of methods for predicting far-field noise of jets is given by Stone.[10] He shows that the spectra for hot stationary jets can be collapsed into a family of equivalent cold jets at different values of the angle θ, the angle which the observer makes with the forward jet axis. To account for jet temperature and Mach number effects, an equivalent angle θ' is introduced, while the Strouhal number is replaced by a modified value

$$S_t{}^* = S_t \, (T_j/T_a)^{0.4(1+\cos\theta')}$$

Of particular interest is the fact that, when θ' is 150 deg, i.e., equivalent to 30 deg from the aft axis, the spectrum peaks at a modified Strouhal number of about 0.3, while the overall sound pressure level reaches its highest value. Thus the far-field noise at 30 deg to the aft axis, the near-field free-flow static pressure, and the fluctuating pressure on the surface of any wall on which the jet impinges, have similar spectra for cold circular jets.

III. Experimental Facility and Instrumentation

Quarter-Scale Model

A schematic arrangement of the quarter-scale model is shown in Fig. 1. The curved airfoil is of mahogany, and contains instrumentation ports for pressure measurements whose positions are indicated in Fig. 2. It is a scale model of the full-scale airfoil, which is built of aluminum alloy. The 234 mm by 42 mm rectangular nozzle is a scale model of the full-scale outer nozzle, but is built of fiberglass. The remainder of the model is not to scale. A fiberglass adapter section connects the nozzle to a plenum chamber, which is filled with soda straws for flow straightening. The plenum is fed with air from a blower through a muffler designed to eliminate a broad band of noise due to blade passing frequencies in the blower. There are provisions for a core nozzle to represent that on the JT-15D, in which case the bypass air is fed through a side opening in the plenum. The core nozzle has not been installed for any tests made to date, but a speaker was installed in the side opening of the plenum in a test reported earlier[9] in which the effect of exciting acoustical modes was studied. Improvements to the quarter-scale model since the previous work have included a conical diffusion section into the plenum, and a larger blower, which has increased jet velocities from 22 m/s to 45 m/s.

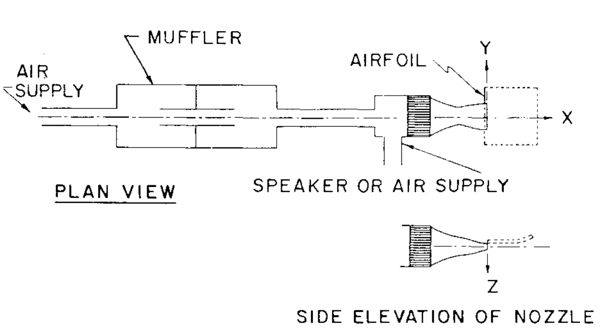


Fig. 1 Schematic of quarter-scale model.

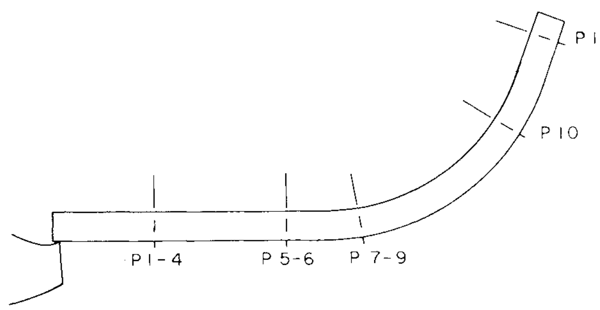


Fig. 2 Locations of surface pressure probes.

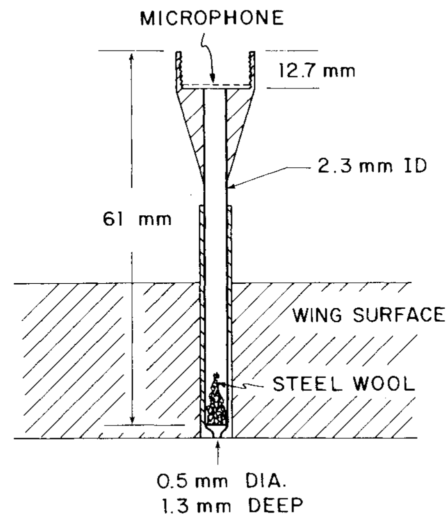


Fig. 3 Surface probe with microphone attachment.

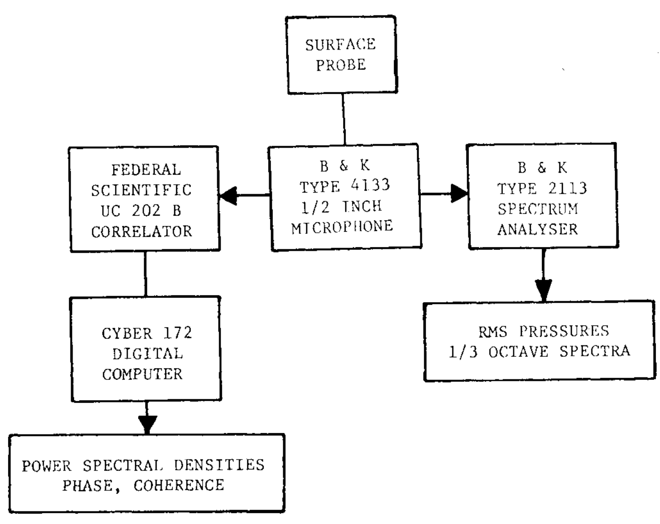


Fig. 4 Data flow in instrumentation system.

Instrumentation

A typical surface pressure probe is shown in Fig. 3. This consists of a 0.5 mm hole in the surface connected to a ½-in. B&K microphone through a conical adapter from a B&K probe kit. A schematic arrangement of the instrumentation is shown in Fig. 4, in which the signals from one or two microphones can be analyzed. For quick analysis of one microphone, a B&K 2113 Spectrum Analyzer is used to obtain uncorrected one-third octave spectra or overall levels of the unsteady pressures. Alternatively, the signals from one or two microphones can be fed into a Federal Scientific (now Nicolet) 512-point digital correlator, whose output can be read into a computer through a remote terminal. By computing Fourier transforms of the correlations, the computer obtains power-spectral-densities of the surface pressures, corrected for probe transfer function if this is known. Also, when there are two probes, cross correlations, relative phase angles, relative amplitudes, and coherences are obtained. Improvements in the instrumentation since the earlier work have included conversion from ⅛-in. to ½-in. microphones, which has eliminated problems with the very sensitive ⅛-in. adapters, and replacement of lengths of plastic tubing with the much shorter metal tubing shown in Fig. 3. However, the most important improvement has been the development of a calibration chamber, in which a probe can be subjected to pink noise alongside a ½-in. microphone, thus, the resulting transfer function can be measured and stored for later use. A typical transfer function obtained in this manner is shown in Fig. 5, it is for the surface probe shown in Fig. 3 with steel wool inserted as shown.

Using the calibration system just described, accurate power spectral densities of surface pressure can now be measured on the quarter-scale model, whereas, earlier, it had only been possible to measure relative phase angles and amplitudes. Thus, while the earlier work emphasized the large-scale structure of the rectangular jet, the present paper is concerned with direct scaling effects on power-spectral-densities.

IV. Evaluation of Scaling Laws

The quarter-scale model has been used in a direct evaluation of the scaling laws by comparing overall levels and power-spectral-densities of surface pressures measured on the model with those reported by Mixson et al.[11] and Schoenster et al.[12] for the full-scale facility. Further information on the latter was obtained from a report by Shivers and Smith.[13] Although the rectangular nozzle and the airfoil were carefully scaled, the following discrepancies are noted.

1) The model did not have a core nozzle so that perfect agreement could only be obtained with perfect mixing of the hot core air of the JT-15D in the remaining 470 mm before emerging from the rectangular outer nozzle.

2) All of the model tests are with a cold nozzle, whereas the full-scale tests are with a hot core and a cold bypass nozzle.

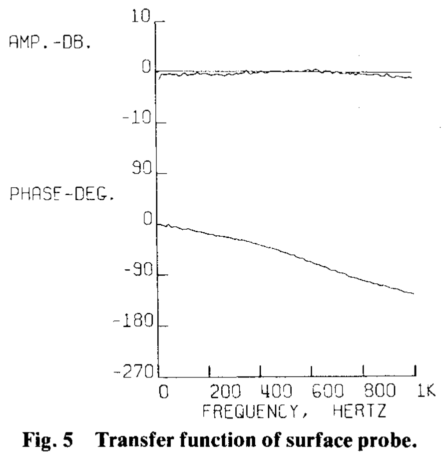


Fig. 5 Transfer function of surface probe.

Table 1 Test variables

Variable	Full scale max.-min.	Model
D_{eq} (m/m)[a]	0.357	93.4
U_j (m/s)	277.4/96.6	45.0
q_j(N/m^2)	22300/3280	1190
M_j	0.559/0.214	0.13
T_j (°K)	611.1/505.6	300
$R_{Deq}(10^6)$	3.72/1.65	0.401

[a] By Stone's[10] formula.

3) The model jet was limited to a Mach number of 0.13, whereas the full-scale test Mach numbers ranged from 0.21 to 0.56.

4) The Reynolds number for the full-scale tests was from four to nine times that of the model tests.

Test Variables

A list of test variables is given in Table 1. This includes both maximum and minimum values for the full-scale case.

Power-Spectral-Density Comparisons

Comparative power-spectral-density plots of the model and of the full-scale article were used to evaluate potential scaling laws. First, it was assumed that there were only two significant scaling parameters. These were the Strouhal number and the pressure coefficient. Accordingly, the following relationships were established to predict full-scale values (subscript *PFS*) from model data (subscript *M*) and full-scale values (subscript *FS*):

$$f_{PFS} = f_M \times (U_{jFS}/U_{jM}) / (D_{eqFS}/D_{eqM})$$

$$LPSD_{PFS} = LPSD_M - 10\log_{10}(f_{PFS}/f_M) + 20\log_{10}(q_{jFS}/q_{jM})$$

Of the preceeding two equations, the first gives the frequency f on the assumption of equal Strouhal numbers, while the second gives the power-spectral-density level *LPSD* expressed in decibels. This is related to the power-spectral-density G_p (Pa^2/Hz) by the equation:

$$LPSD = 10\log_{10}G_p + 94 \quad \text{dB (re: } 2\times10^{-5}\text{ Pa}/\text{Hz}^{1/2})$$

Of the two correction terms in the second equation, the first renormalizes the density following a change in frequency scale, while the second introduces the assumption of equal pressure coefficients. When an attempt was made to predict the full-scale spectra from model data, and these were compared with the full-scale spectra taken at maximum conditions, it was found that the predicted spectral peaks were about 1.6 times too high in frequency. On the other hand, the same prediction technique using the full-scale spectra taken at other than maximum conditions gave results which were in close agreement.

The possibility of experimental error in measuring frequencies was rejected, and the error was obviously much too large to be accounted for as dimensional, leaving only the possibility that failure to account for one of the other three scaling parameters is responsible. Of the three, the Reynolds number of the full-scale article varies from four to nine times the model value, while the Mach number varies 1.6 to 4.6 times, neither of these seem consistent with the almost constant 1.6:1 error. However, the temperature ratio of the full-scale jet varies between 1.7 and 2.0, while it is 1.0 for the model, a range of variations which does seem to be consistent with the observed results. Following the approach suggested by Stone for far-field noise prediction, a tentative correction to the Strouhal number was obtained as follows:

$$St^* = St \times (T_j/T_a)^{0.75}$$

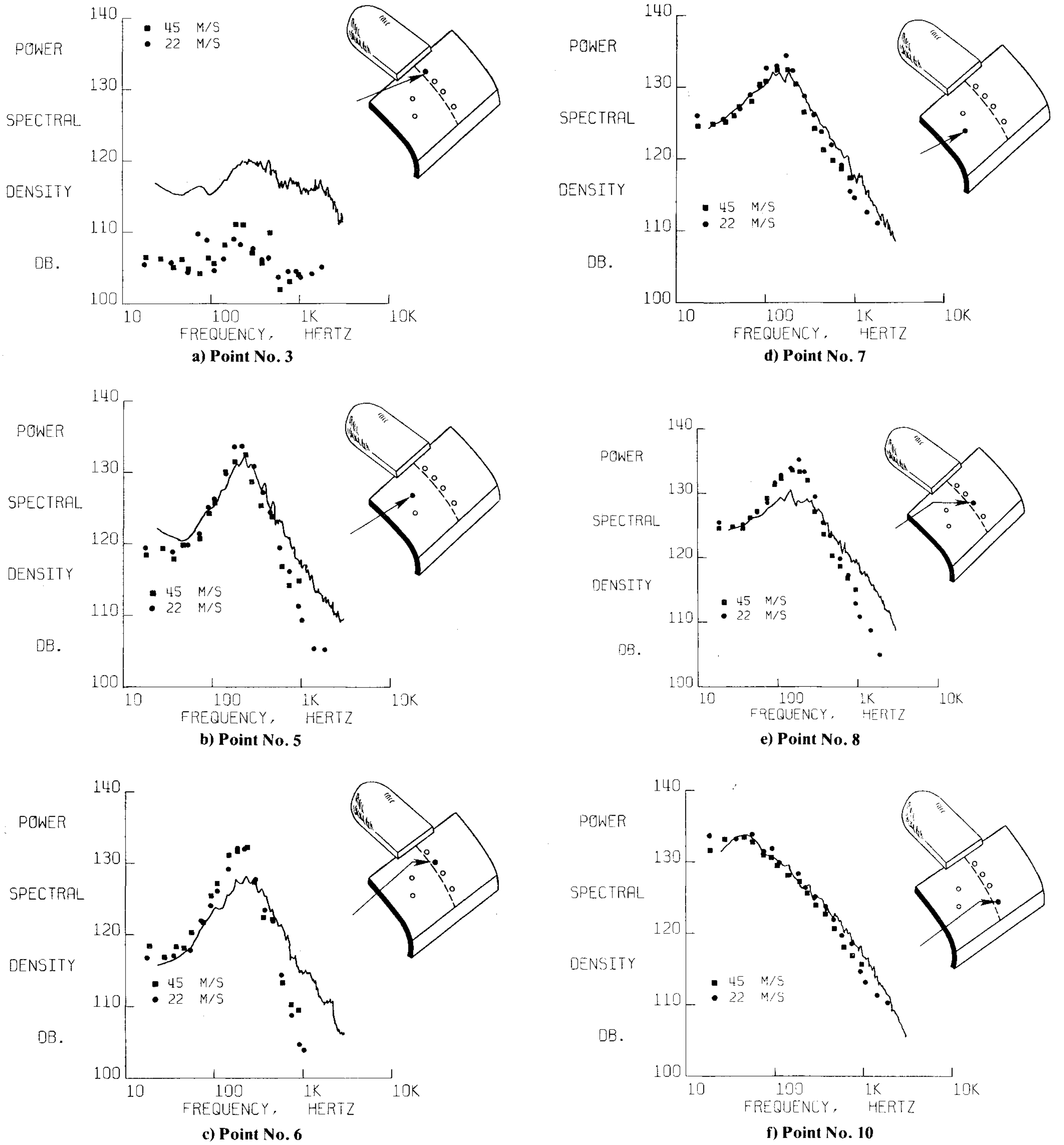


Fig. 6 Comparison of model prediction vs full-scale P.S.D.

so that the predicted frequency became

$$f_{PFS} = f_M \times (U_{jFS}/U_{jM}) / \{ (D_{eqFS}/D_{eqM}) \times (T_j/T_a)^{0.75}_{FS} \}$$

the equation for *LPSD* remaining formally as before.

Comparisons of spectra scaled according to the last method are shown in Fig. 6 for the six points on the airfoil indicated in Fig. 2. Good agreement is seen for the furthest point on the jet centerline (P10) and for the two off to the side (P5 and P7). Two closer points on the centerline fail to predict the higher-frequency spectral components, while overpredicting the peak values; this could indicate the need for a core jet in the model. The greatest disparity between model and full-scale results is evidenced at the closest point to the nozzle exit plane (P3). The model spectrum, in addition to being lower in level, fails to reproduce the double peaked characteristic of the full-scale spectrum. However, other tests showed that this spectrum was very sensitive to such test variables as the nozzle to airfoil gap, the jet impingement angle, and the geometry of a deflector mounted on the nozzle. To illustrate, Fig. 7 presents the effect of unsealing the gap between the nozzle and airfoil surface. This effect is, in turn, dependent on impingement angle which indicates the uncertainty as to the source of disagreement between model and full-scale results.

Possibly, some of the previously noted discrepancies are due to the failure to represent the full-scale engine noise spectra in the model plenum chamber. In fact, the authors showed earlier[9] that some frequencies excited in the plenum

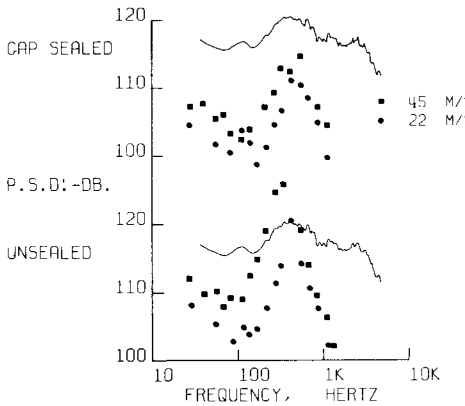


Fig. 7 Comparison of model prediction vs full-scale P. S. D. at point No. 3 showing effect of gap seal.

chamber became amplified by as much as 20 dB in the jet. However, it is believed that the effects of a core jet, or of detailed configuration changes are more likely candidates.

Should it prove essential, in some cases, to model the core nozzle, it will be difficult to do this with a cold jet. The problem is that, to maintain the proper kinetic scaling, i.e., to maintain the proper frequency ratio between the two large-scale structures, the temperature corrected Strouhal numbers must be scaled for the core and outer nozzles. At the same time, dynamic scaling is required, so that pressure coefficients must be scaled. These requirements cannot be met simultaneously unless the air density in the core is reduced, either by heating the core air, or by using a lighter gas.

rms Pressure Coefficient Comparisons

The preceding scale changes in the spectra were made on the assumption that the rms pressure coefficient remains constant, as can be demonstrated readily, since by definition

$$c^2_{prms} = \frac{1}{q_j^2}\int_0^\infty 10\frac{(LPSD\text{-}94)}{10}\,\mathrm{d}f$$

The validity of the preceding assumption was checked separately by plotting c_{prms} for all of the available experimental points on the model and the full-scale article against the Mach number. These plots are shown in Fig. 8 for some of the instrumentation ports of Fig. 2. With the exception of point 3, variations are of the order of 1 dB or less, and show no discernible trends, the discontinuities at the boundaries between model and full-scale data being no larger, despite the 4:1 jump in Reynolds number, and the 1.7:1 jump in temperature ratio which occurs here. Results obtained at point 3 indicate low model values relative to full scale; however, as was noted earlier, this point was sensitive to local details, such as whether the gap was sealed or not, and what the impingement angle was.

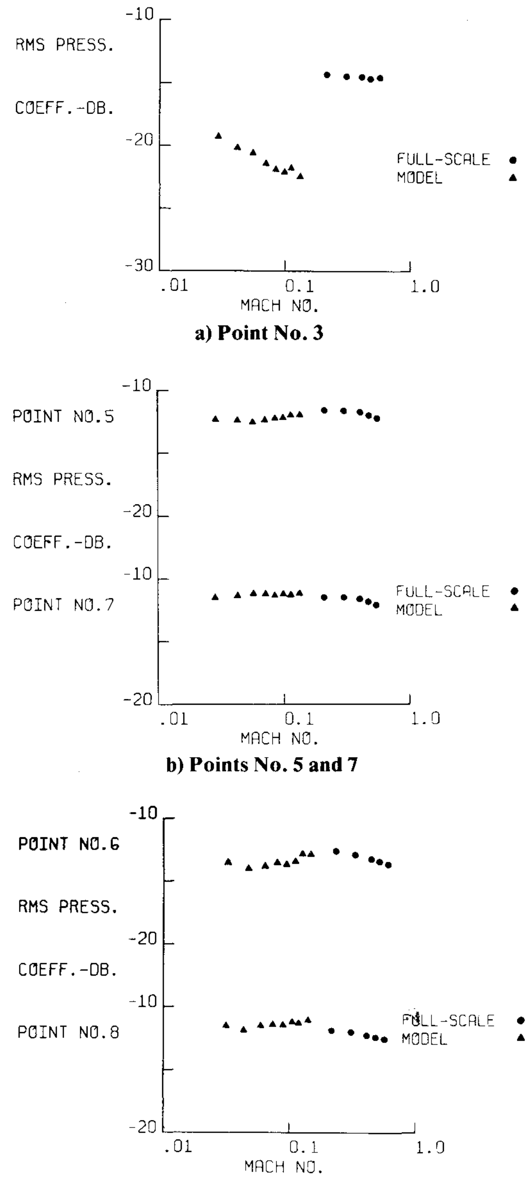
Near-Field Pressures and Far-Field Noise

Similarities between near-field pressure spectra and far-field noise spectra for circular jets have already been noted, the best comparison being made when the far-field data are taken at 30 deg from the aft jet axis. However, the temperature correction given by Stone for far-field noise is angle dependent, and only agrees with the tentative near-field correction for an angle of 30 deg to the forward axis. Therefore, it does not seem possible to carry this comparison any further.

Insofar as noncircular jets are concerned, Stone shows that they can be compared with circular jets if an equivalent diameter is computed. It does not seem possible to collapse near-field pressure data in the same way for the simple reason that the spectral peak frequency in a noncircular jet varies with distance from the jet exit, whereas it remains fixed for a circular jet. As an illustration of this, a local equivalent diameter d_{eq} was determined by assuming a Strouhal number of 0.3 at the spectral peak, so that

$$d_{eq} = 0.3\ U_j/f_{\text{peak}}$$

This is shown plotted in Fig. 9. It is seen that close to the nozzle exit, the equivalent diameter is close to the depth of the



a) Point No. 3

b) Points No. 5 and 7

c) Points No. 6 and 8

Fig. 8 Model and full-scale dependency on Mach number.

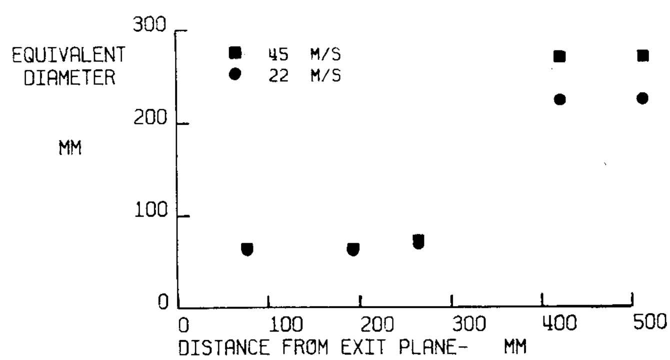


Fig. 9 Equivalent diameter of rectangular jet vs distance from nozzle exit.

nozzle, at 42 mm, but that, at a greater distance, it approaches Stone's D_{eq} value of 357 mm. Thus, the large-scale structure appears to consist of vortices whose diameters start at the nozzle depth, and that these either die out and are replaced by larger vortices whose diameters relate to the far-field noise, or they grow by coalescence.

Conclusions

Scaling Laws

Of the five possible scaling parameters for jet impingement pressures, the results presented here support the conclusion that the Reynolds number and the Mach number, assuming subsonic jets, can be ignored in the scaling process. Of the remaining three, there is some indication that these can be reduced to two, the modified Strouhal number and the pressure coefficient. However, the validity of the temperature correction applied to obtain the modified Strouhal number is uncertain, and, since the experiments reported in this paper were on cold jets, little could be done to clear this up.

Effective Diameter

It was noted that the apparent equivalent diameter of the vortices constituting the large-scale structure is initially equal to the smaller rectangular dimension of the nozzle, but that this diameter increases as the flow moves away from the nozzle. Thus, it may prove difficult to relate pressure spectra in jet impingement by jets of different geometries, and the concept of a single equivalent jet diameter for a noncircular nozzle may not be viable.

Core Nozzle

There was some indication that the effect of a core nozzle may be seen in the higher-frequency spectral components. It will prove difficult to design cold jet models of coaxial jets, when the full-scale version consists of a hot core and cold jet.

Engine Spectra

No conclusive evidence was found to indicate the need for representing the jet engine noise spectra in the plenum chamber of the model jet.

Acknowledgment

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