COMPARISONS OF SHOCK NOISE PREDICTIONS WITH FLIGHT DATA

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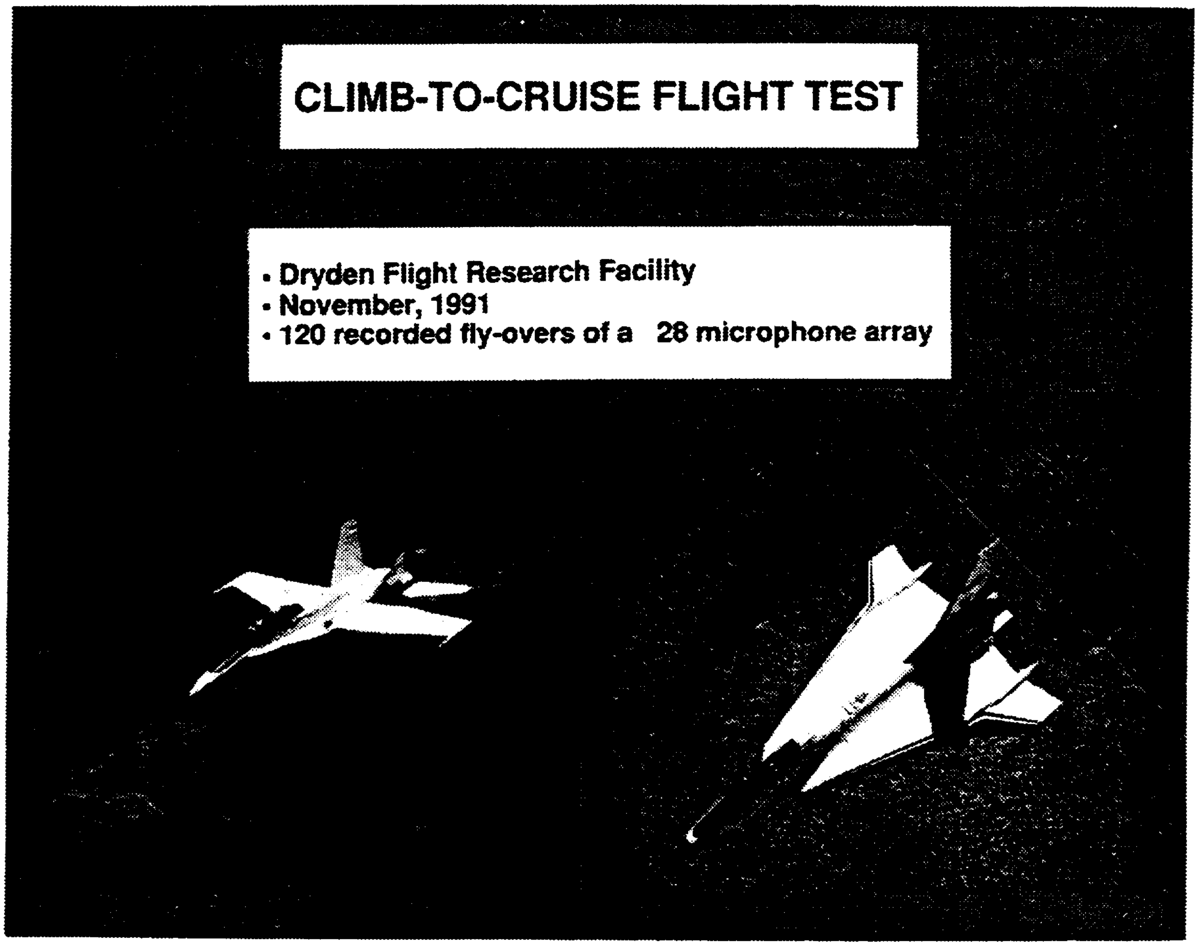
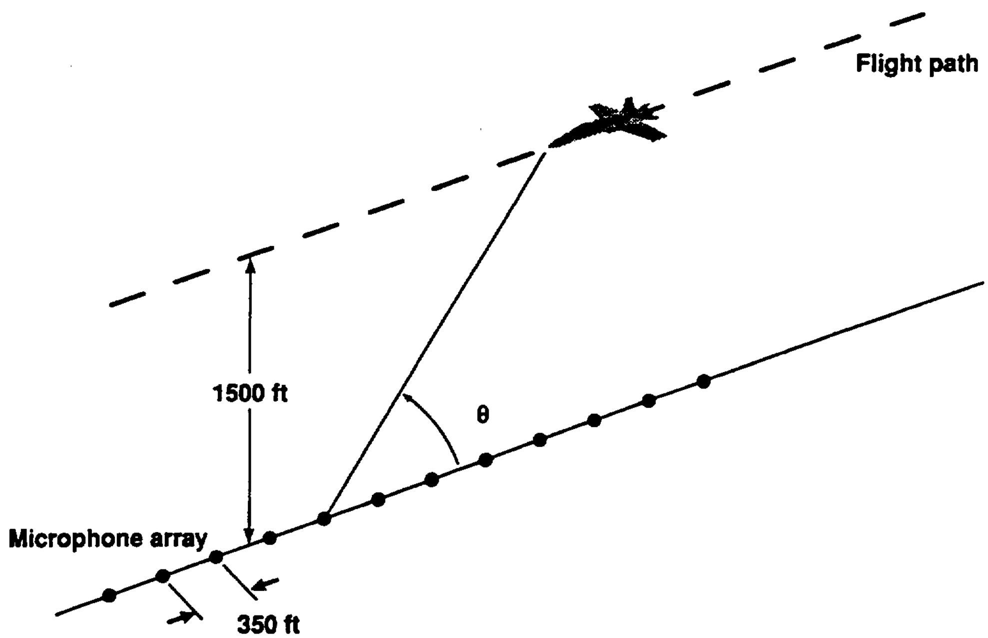


A flight test was performed at NASA Dryden Research Center in November 1991 utilizing both F18 and F16 aircraft. These flights were designed to provide (1) acoustic data that could be extrapolated to that of an HSCT at various points of its climb-to-cruise operation and (2) a data base for noise from a supersonic jet exhausting from an aircraft moving at high subsonic speeds. This presentation utilizes data obtained from these flyovers to evaluate predictions of broadband shock noise from supersonic jets in flight.

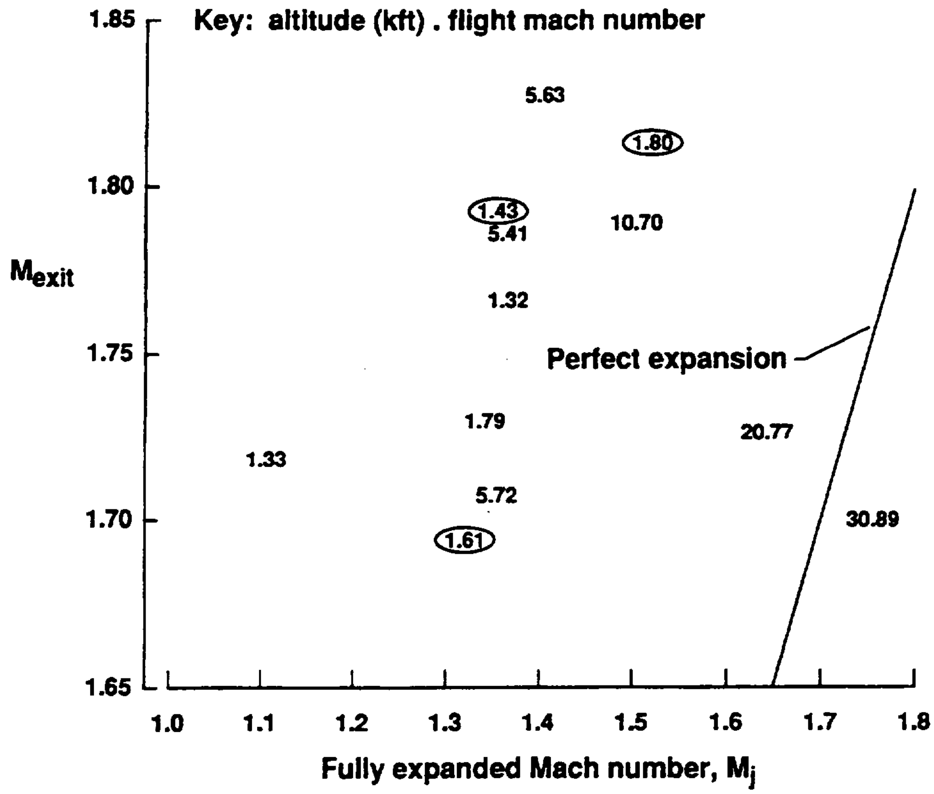
The F18 is particularly suitable for flyovers of shock noise since it can be flown with one engine at flight idle. The second engine can then be operated at a pressure high enough to produce a supersonic nozzle exhaust and still maintain an unaccelerated, level flyover.

F- 18 FLYOVER TEST SETUP



The flight data that will be shown come from constant speed flyovers of an array of 12 microphones by an F18 operating with one engine at flight idle, at an altitude of approximately 1500 feet. Aircraft tracking allowed for ensemble averaging of the 12 microphones and a weather balloon provided the parameters required for atmospheric effects.

NOZZLE CONDITIONS FOR F-18 FLYOVERS



The nozzle operating conditions of the powered engine that were obtained during flight testing of the F18 are shown in this chart. For a given flyover, a data point i given in terms of the altitude in kft followed by jet fully expanded Mach number vs the nozzle exit (design) Mach number. The sloped line on the right represents the fully expanded condition, and shows that the powered nozzle is operating overexpanded in all but a single flight condition (30 kft altitude). The three conditions for which data will be shown are encircled, they being 1 kft (actually about 1500 ft) flyovers at flight Mach numbers of 0.42, 0.61, and 0.80.

SUPERSONIC JET BROADBAND SHOCK NOISE FLIGHT DATA VS PREDICTION

Flight Data

- **F-18 Flyover, 12 Microphone Ensemble Average**
- **Single Supersonic Overexpanded Jet**
- **Altitude ~ 1500 Feet**
- **Flight Mach Numbers 0.43, 0.61, 0.80**

Tam Theory

- **AIAA Journal, 10/92**

Model Data With Point Source Flight Corrections

- **Frequency - Doppler Shift**
- **Amplitude - Convective Amplification**

This chart summarizes the flight data to be presented and the predictions to which the data will be compared. The majority of the comparisons will be to Tam's theory of broadband shock noise. The latest formulation of this theory, which is directly applicable to an aircraft flyover, is given in last months AIAA journal. Older formulations for predicting broadband shock noise are based on correlations of model scale data from convergent nozzles (i.e., underexpanded jets) and hence cannot be compared directly to the data. However, an attempt is made in this presentation to evaluate the flight corrections of the older formulations that include a Doppler shift of the frequency and a convective amplification of the amplitude of the broadband shock noise.

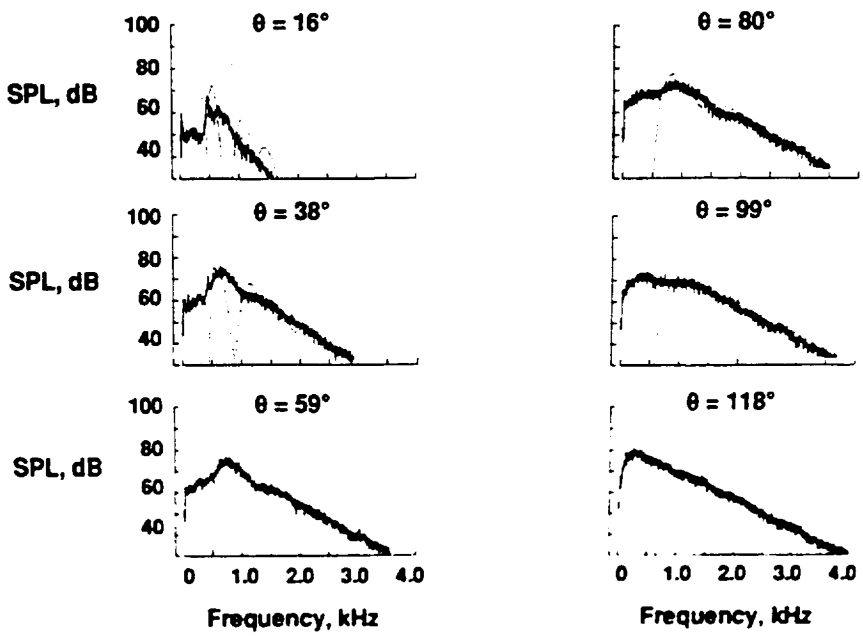
ELEMENTS OF TAM THEORY OF BROADBAND SHOCK NOISE

- **Large Scale Structures/Instability Waves Interacting with Shocks in Jet Plume**
- **Multiple Scales Model of Shock Cell Structure**
- **Multiple Modes Give Wide Frequency Distribution**
- **Applicable to Convergent-Divergent Nozzles**
- **Analytical Results**

The Tam theory of broadband shock noise involves the interaction of the jet large scale turbulent structures or instability waves with the shock structure in the jet plume. A multiple scales model of the shock cells yields a solution consisting of multiple modes that gives a wide frequency distribution for the broadband noise. Unlike the older methods that are valid only for convergent nozzles, this formulation also applies to convergent-divergent nozzles. The result is analytical and hence does not require correlations from a data base inherent to the older methods.

COMPARISON OF FLIGHT SPECTRA WITH TAM THEORY

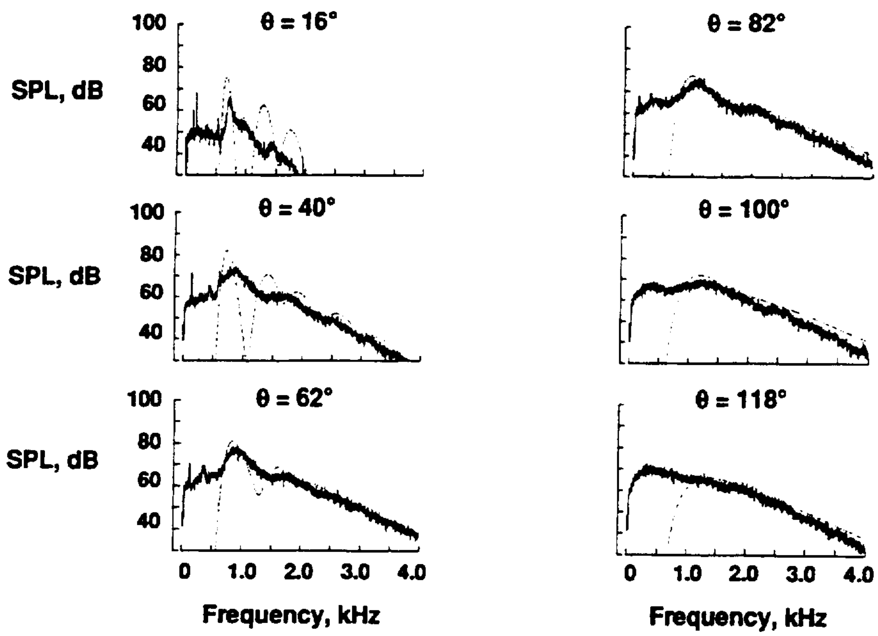
Flight Mach number, 0.43 $M_j = 1.35$
Altitude, 1440 ft $M_{exit} = 1.79$



The next three charts show direct comparisons of the narrow band spectra (2 Hz bandwidth) between the flyover data and the Tam predictions. The solid lines are the data as measured, whereas the dotted curves are Tam's predictions modified by the propagation losses appropriate for the weather conditions that were measured at the time of the flyover. The typical spectrum shows a low frequency broadband component due to jet mixing noise followed by a peaked broadband shock noise spectrum at higher frequency. In this chart of the data from the Mach .43 flyover, the curves on the right sown an excellent agreement in the broadband shock noise portion of the spectra at angles close to 90 degrees. At the further upstream shown on the left, the spectral width of the different modes contributing to the Tam spectra become narrower, resulting in a highly peaked disjoint curve, a behavior which incidentally is also present in Tam's predictions for a static jet.

COMPARISON OF FLIGHT SPECTRA WITH TAM THEORY

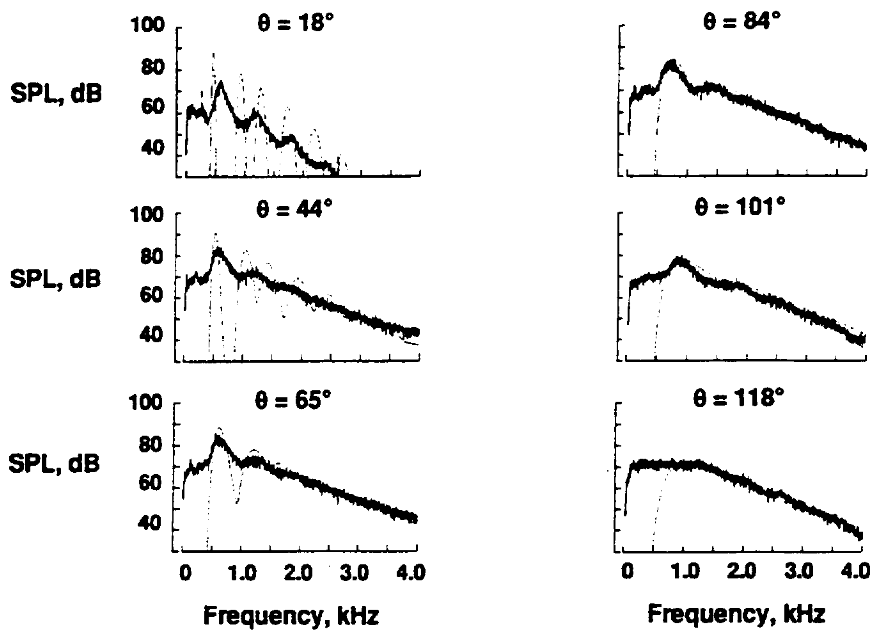
Flight Mach number, 0.61 **M_j = 1.32**
Altitude, 1430 ft **M_{exit} = 1.69**



Similar results are seen for the spectral comparisons at the flight Mach number of 0.61. The good agreement between flight data and Tam theory near the overhead position is evident, as is the mode separation of the theory at small angles.

COMPARISON OF FLIGHT SPECTRA WITH TAM THEORY

Flight Mach number, 0.80 $M_j = 1.51$
Altitude, 1420 ft $M_{exit} = 1.81$



More of the same is seen in this chart for a flight Mach number 0.80. There is excellent agreement of both the peak frequency and the amplitude of the broadband shock noise near 90 degrees. The spectral widths of the contributions of individual modes at the lower angles are even narrower than those at the lower flight speeds.

BROADBAND SHOCK NOISE "POINT SOURCE" FLIGHT PREDICTIONS

Peak Frequency: Doppler Shift of Model Scale Directivity

$$f_p(\theta) = \frac{f_p(\text{flight data at 90 degrees})}{(1 + M_c \cos\theta)(1 - M_f \cos\theta)}$$

Model Scale Static Directivity Factor — Doppler Frequency Shift

Peak Amplitude: Convective Amplification

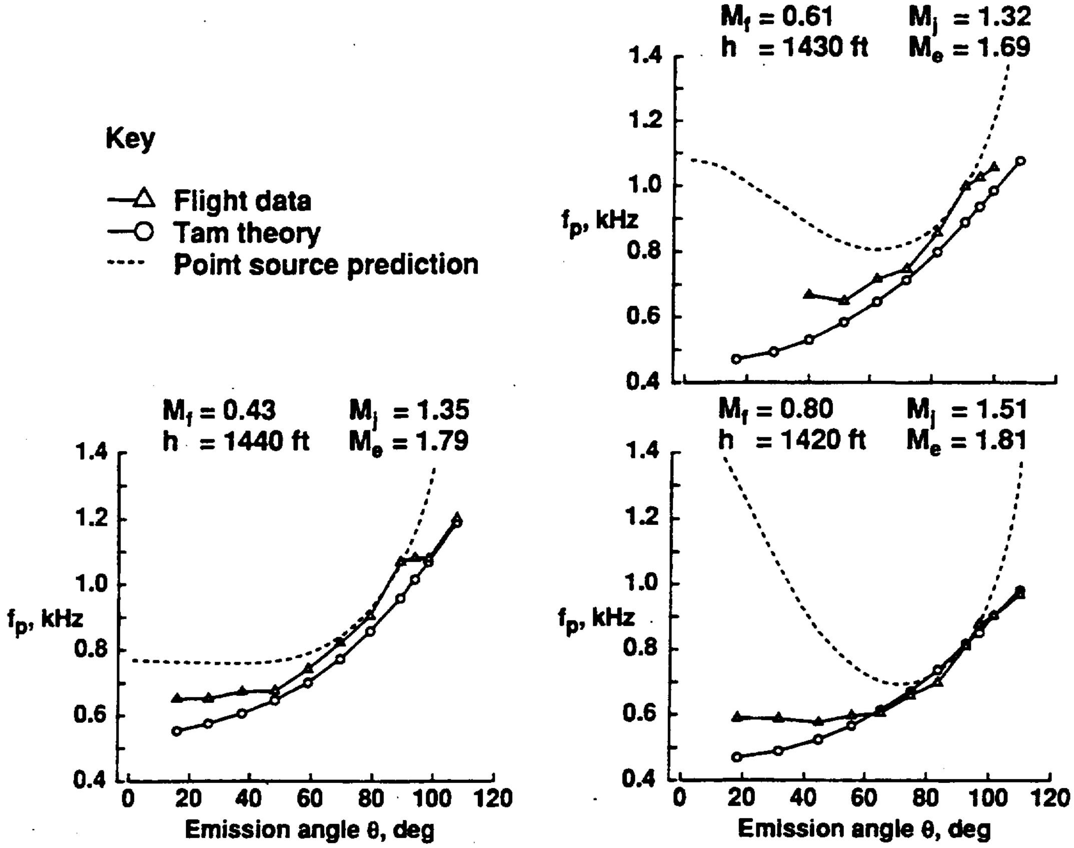
$$SPL(\theta) = SPL\ (\text{flight data at 90 degrees})$$

- Additional Atmospheric Absorption
- Additional Spherical Spreading

$$+\ 10 \log (1 - M_f \cos\theta)^{-4}$$

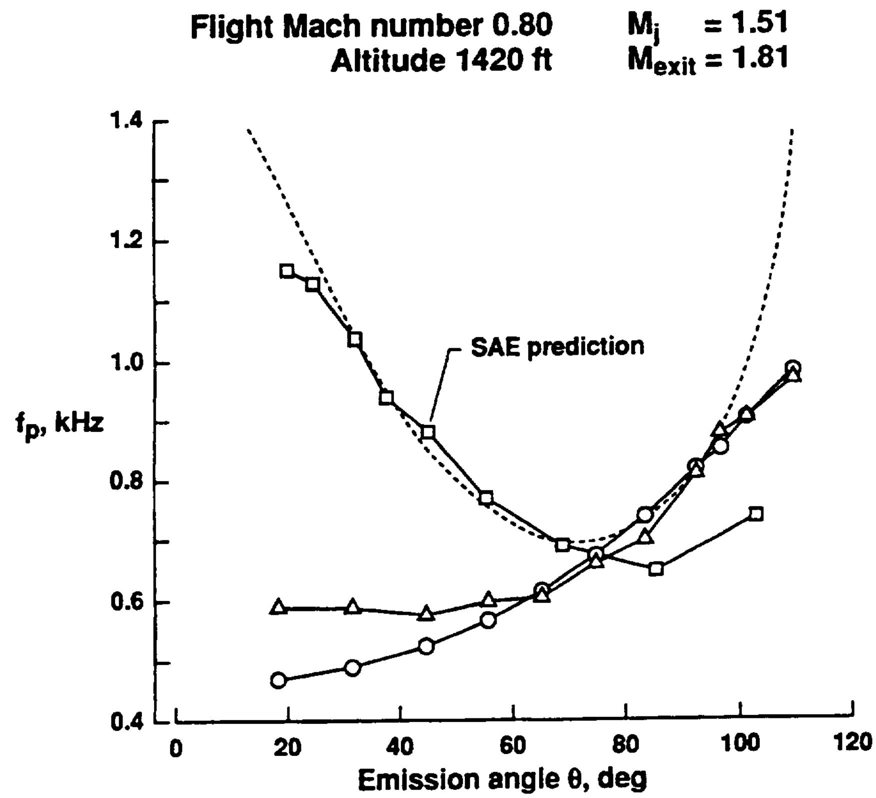
Comparisons will now be made of the variations with emission angle of both the peak frequency and the peak amplitude of broadband shock noise. In addition to the flight data and Tam' theory, computations that utilize the flight corrections that are used in the older shock noise predictions (e.g., SAE method, Stone's method) will be shown. These flight corrections are derived from analysis of an acoustic point source in motion and include a Doppler shift of the frequency and a convective amplification of the amplitude. The frequency variation to be shown uses the measured peak frequency from the flight spectra at 90 degrees, the known static directivity that has been determined from model data and is a function of the eddy convection Mach number in the jet, and the Doppler frequency shift. The peak amplitude variation also uses the value obtained from the flight data at 90 degrees, additional propagation losses due to the observer at theta being at a distance further than that at 90 degrees, and the convective amplification, which includes a fourth power of the Doppler factor.

PEAK FREQUENCY OF BROADBAND SHOCK NOISE



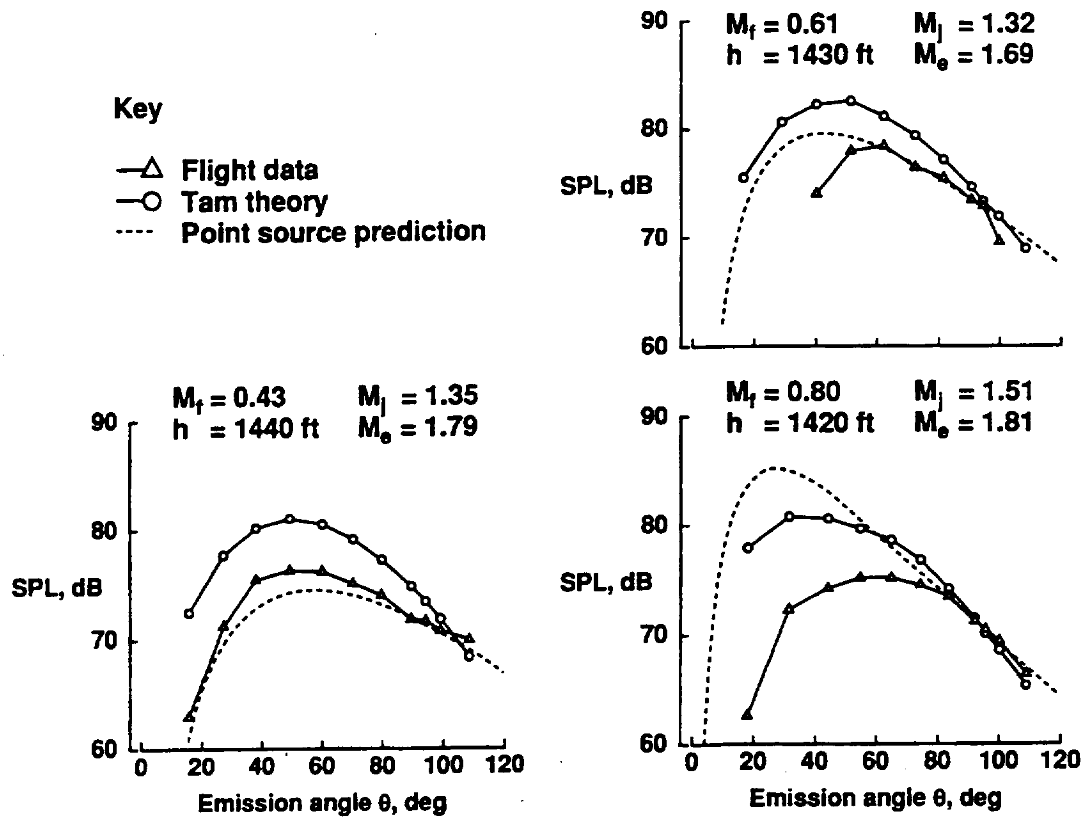
The variation of the peak frequency of the broadband shock noise with emission angle is shown for each of the three flight Mach numbers. A comparison between the flight data and Tam's theory shows the trends to be identical, with the frequency increasing with emission angle in a manner similar to that which occurs for static data. As was seen in the spectra of the previous charts, the measured and predicted frequencies are close, with the Tam theory giving the measured and predicted frequencies, particularly at small emission angles. The frequency variation from the point source prediction has a behavior similar to the other two at the low flight Mach number. However, as the Mach number is increased, the Doppler shift becomes more pronounced, resulting in a frequency variation at small emission angles that is similar to that for an acoustic point source but contrary to the measured flight results for broadband shock noise.

PEAK FREQUENCY OF BROADBAND SHOCK NOISE



A confirmation of the frequency variation of the older shock noise predictions is shown in this chart. The older methods are designed for underexpanded jets from convergent nozzles and hence do not apply to the overexpanded jets from the convergent-divergent nozzle of the F18. However, a convergent nozzle of the same throat area and flight conditions as the 0.80 Mach number flight is about as underexpanded as the flight nozzle was overexpanded (i.e. they have similar shock cell strengths). Inputting this into the ANOPP implementation of the SAE shock noise method yields spectra whose peak frequency variation has been superimposed on the results of the last plot of the previous chart. As expected, the peak frequency trend of the SAE method closely follows that of the point source prediction, indicating that the method does not predict the correct variation of the frequency of broadband shock noise at high flight speeds.

PEAK AMPLITUDE OF BROADBAND SHOCK NOISE



The peak amplitude variations for the three flight Mach numbers are given here. As was seen in the spectra of previous charts, Tam' predicted amplitudes show excellent agreement with the flight data at emission angles near 90 degrees and overpredict the amplitudes at smaller angles. The results from the point source predictions are not as consistent. Recall that, unlike the Tam theory, these predictions are forced to agree with measurements at 90 degrees. In contrast to the flight data which show a similar amplitude variation with emission angle for the three flight speeds, much larger peak amplitudes at small angles are obtained from the point by the convection amplification factor at high speeds. The fact that the measurements do not show this type of increase indicates that a dominating convective amplification factor is invalid as a flight correction to broadband shock noise.

CONCLUSIONS

- **Point Source Flight Predictions Invalid for Broadband Shock Noise at High Flight Speeds**
- **Tam Theory for Broadband Shock Noise in Flight**
  - **Excellent Agreement in Both Frequency and Amplitude at 90 degrees**
  - **Proper Frequency Trend with Emission Angle**
  - **Modification Required for Improved Prediction at Small Emission Angles**

It has been shown that the Doppler frequency shift and the convective amplification factors that result from analyses of acoustic point sources in motion do not apply to broadband shock noise from an overexpanded jet of an aircraft at high subsonic flight speeds. The Tam theory appears to be a much better predictor of broadband shock noise in flight. In addition to predicting both the correct amplitude and frequency distribution at the overhead position of flyovers at flight speeds to Mach 0.8, the correct frequency trend with emission angle was also obtained. Although the theory is not as good in predicting the spectra at small emission angles, the fact that it is analytical in nature should make it relatively easy to modify for improved comparison at the smaller angles.