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THEORETICAL ASPECTS OF SUPERSONIC JET NOISE

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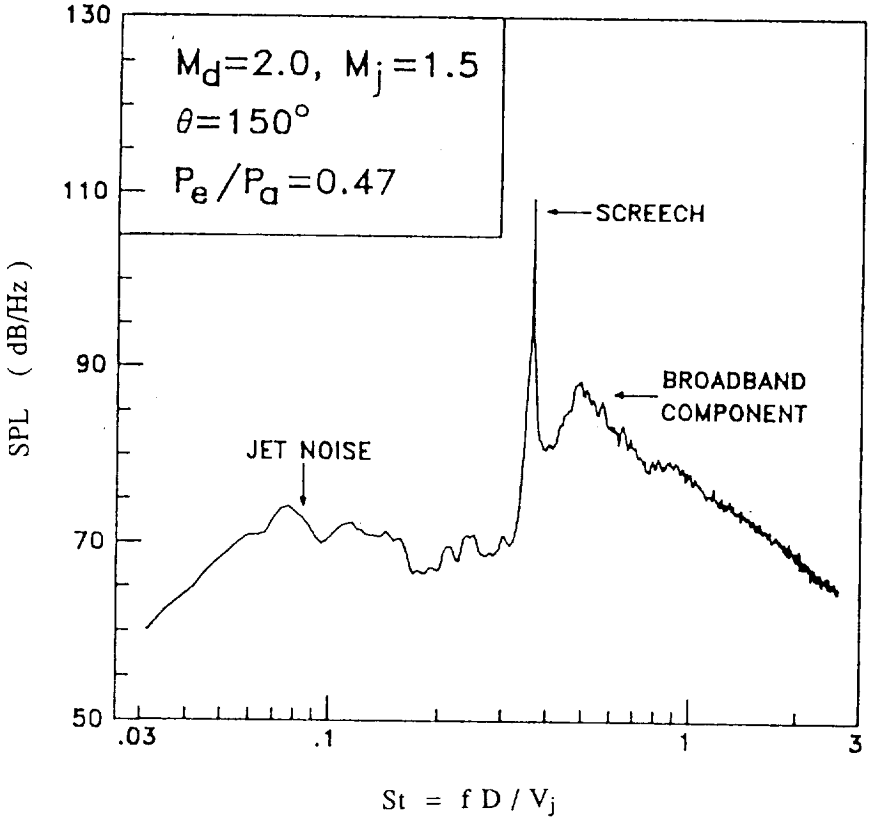
THE THREE COMPONENTS OF SUPERSONIC JET NOISE

The noise of supersonic jets consists of three principal components. They are the turbulent mixing noise, the screech tones and the broadband shock associated noise. The turbulent mixing noise forms the low frequency peak of a typical supersonic jet noise spectrum. The screech tones are sound waves of discrete frequencies. Broadband shock associated noise is the high frequency component of the jet noise spectrum. It is made up of a main peak and sometimes a few secondary peaks at higher frequencies. Experimental observations and theory indicate that the fundamental screech tone frequency marks the low frequency limit of broadband shock associated noise. Both the screech tones and broadband shock associated noise are generated by the presence of a shock cell structure in the jet. For a perfectly expanded jet the total radiated noise is less and comprises of only turbulent mixing noise.

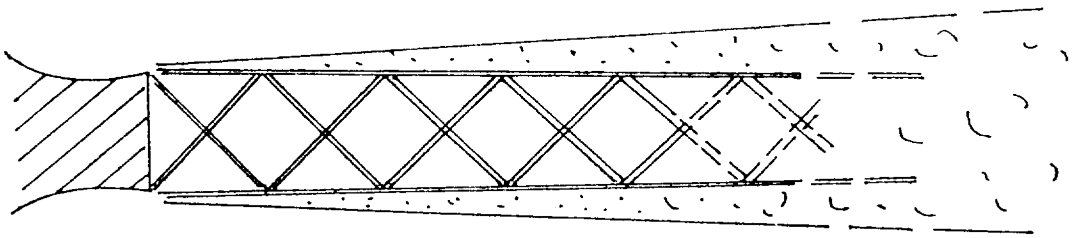


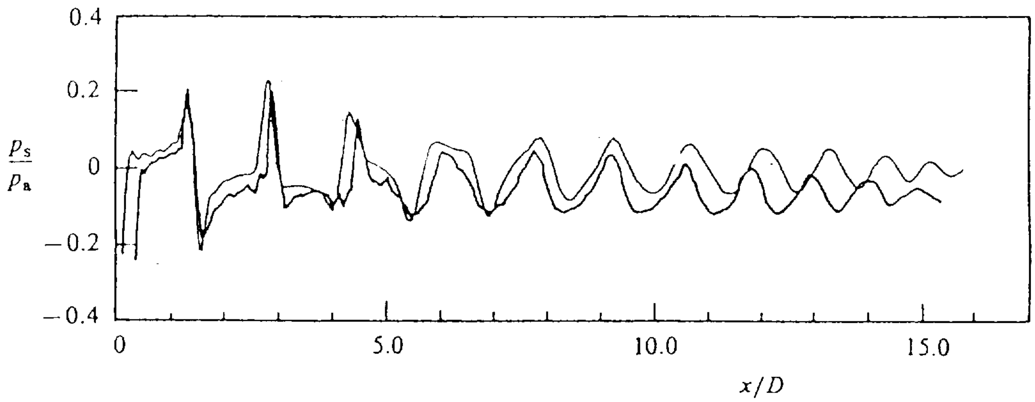
Typical far field supersonic jet noise spectrum

SHOCK CELL STRUCTURE OF IMPERFECTLY EXPANDED JETS

The static pressure at the nozzle exit of an imperfectly expanded jet is not equal to the ambient pressure. To obtain pressure equilibrium at the nozzle lip a shock wave or an expansion fan is formed. The shock or expansion fan allows the gas of the jet to adjust quickly to the ambient pressure. From the nozzle lip the shock or expansion fan propagate across the jet to the mixing layer on the other side. Outside the jet the gas is stationary or in low subsonic motion. Shock or expansion is not allowed. As a result the shock or expansion fan is reflected back at the mixing layer. The reflected expansion fan or shock will continue to propagate downstream bouncing back and forth from one side of the jet to the other. In this way a quasi-periodic shock cell structure is formed. The details of the shock cell structure can be calculated analytically [1] or computationally [2]. Of importance to broadband shock associated noise and screech tone predictions are the gross features of the shock cell structure, namely, the shock cell spacing and pressure amplitude.

QUASI-PERIODIC SHOCK CELL STRUCTURE



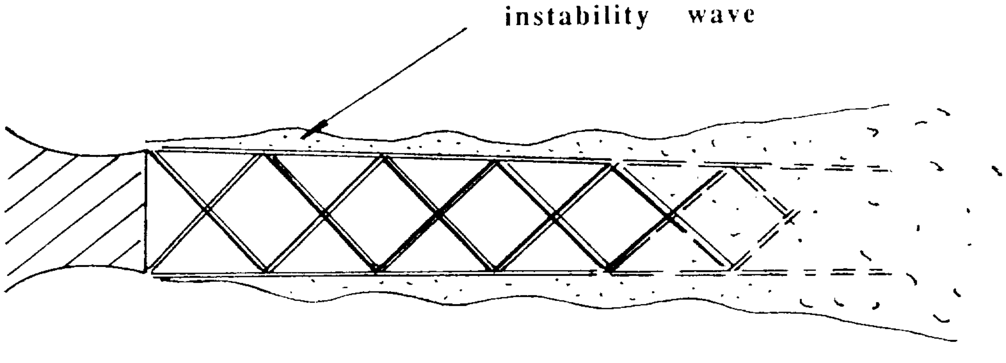


Axial pressure distribution at r/D = 0.38, M_j = 1.82, M_d = 2.0
Measured -- dark line : Calculated -- light line

LARGE TURBULENCE STRUCTURES/INSTABILITY WAVES

One of the most important physical entities in the flow of a supersonic jet which is responsible for noise generation is the large turbulence structures/instability waves. Pictures (see sketch below) of these instability waves are provided in ref. [3]. They are usually called the Kelvin-Helmholtz instability waves. They generally appear in a form with either axisymmetric or helical (flapping) geometry. These instability waves derive their energy from the mean flow. They are also responsible for the mixing and entrainment of ambient gas into the jet flow.

LARGE TURBULENCE STRUCTURES/INSTABILITY WAVES

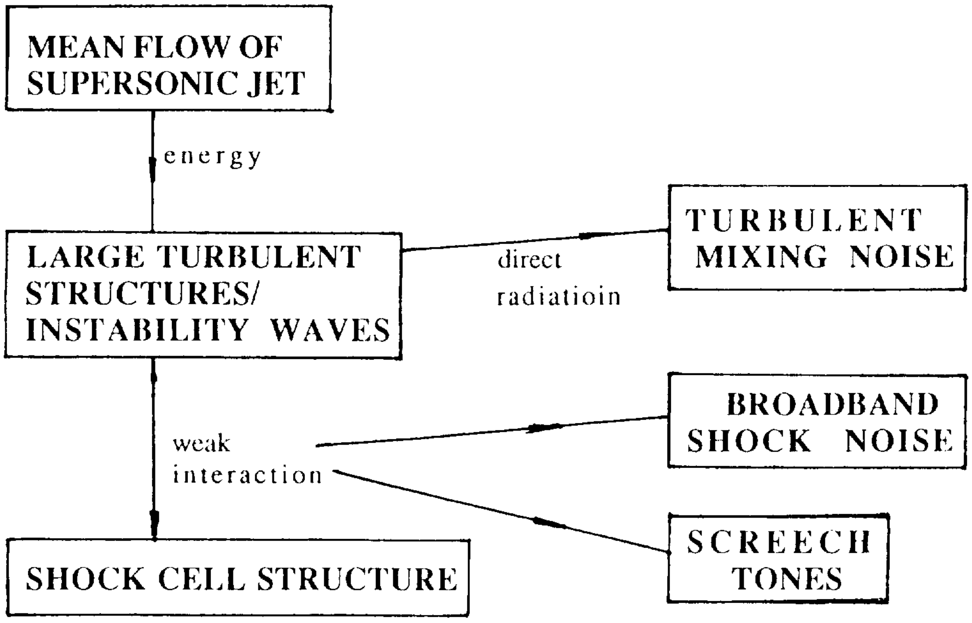


Large scale instability waves in the mixing layer of a supersonic jet excited by upstream sound waves

SUPERSONIC JET NOISE THEORY

There exists now a fairly good understanding of how the three principal components of supersonic jet noise are generated. The crucial element is the large turbulent structures/instability waves of the jet flow. These instability waves extract energy from the mean flow as they propagate downstream along the jet column. The turbulent mixing noise is generated directly by the supersonic components (relative to the ambient speed of sound) of these instability waves. The screech tones and the broadband shock associated noise are generated by the weak interaction of these instability waves and the shock cell structure as the former propagate through the latter.

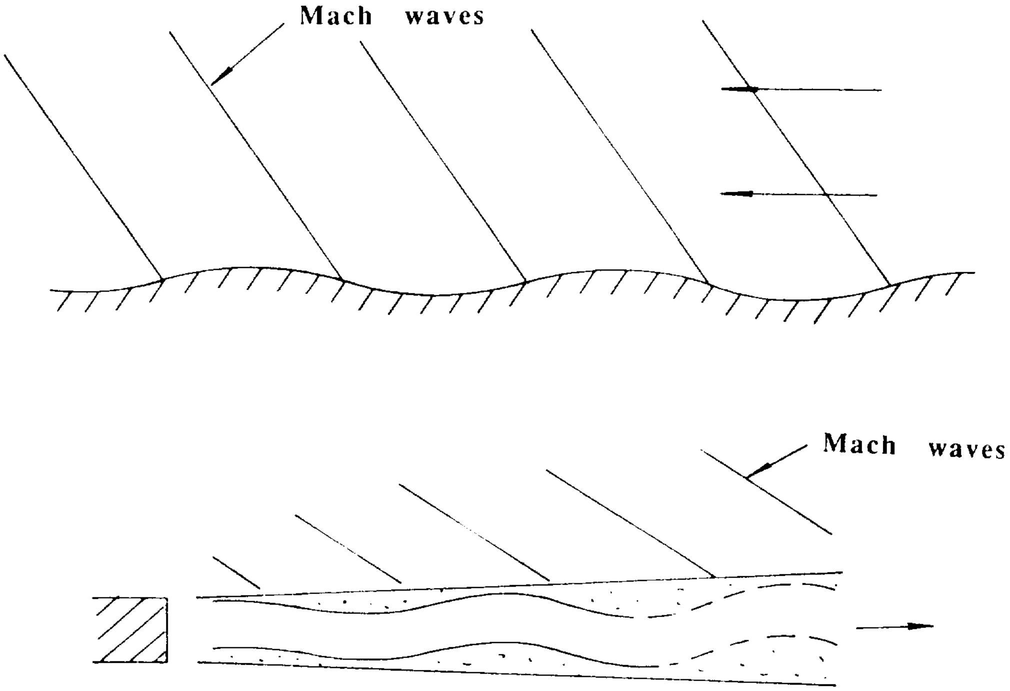
SUPERSONIC JET NOISE THEORY



GENERATION OF TURBULENT MIXING NOISE

To understand how instability waves generate turbulent mixing noise let us remind ourselves the problem of supersonic flow past a solid wavy wall. The solution of this problem suggests that Mach waves are formed. These Mach waves extend to infinity away from the wall indicating that acoustic disturbances are radiated to the far field. Now an instability wave travelling with supersonic velocity relative to the ambient speed of sound is analogous to the problem of supersonic flow past a wavy wall [4]. Mach waves are radiated. The principal direction of radiation is normal to the Mach wave front. The frequency of the radiated sound is equal to the frequency of the instability wave.

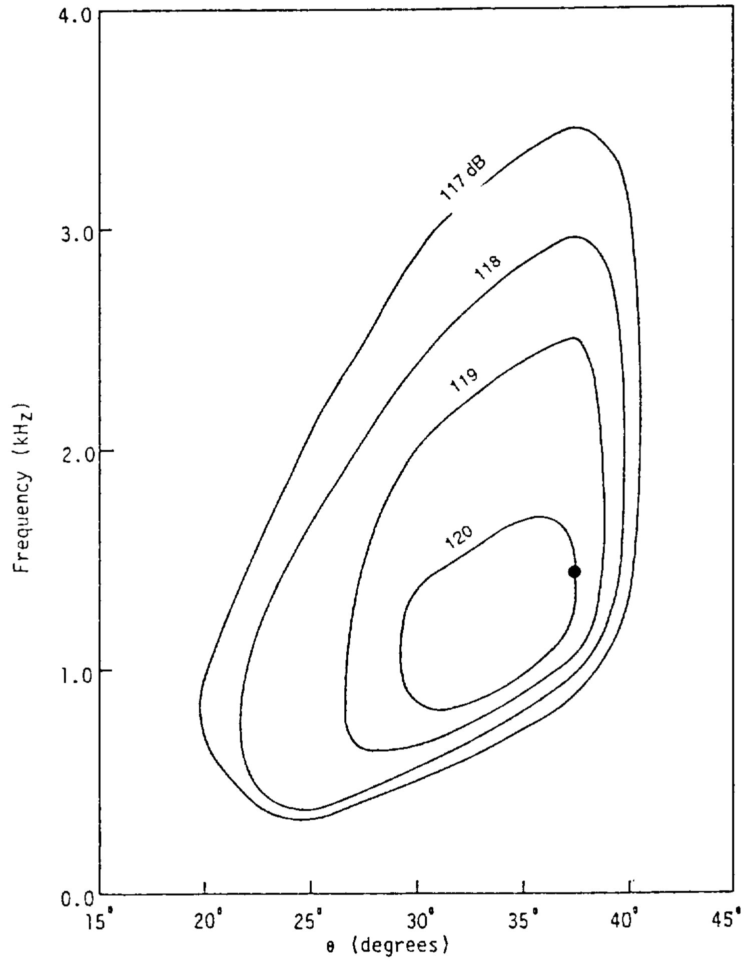
TURBULENT MIXING NOISE



Wavy wall analogy

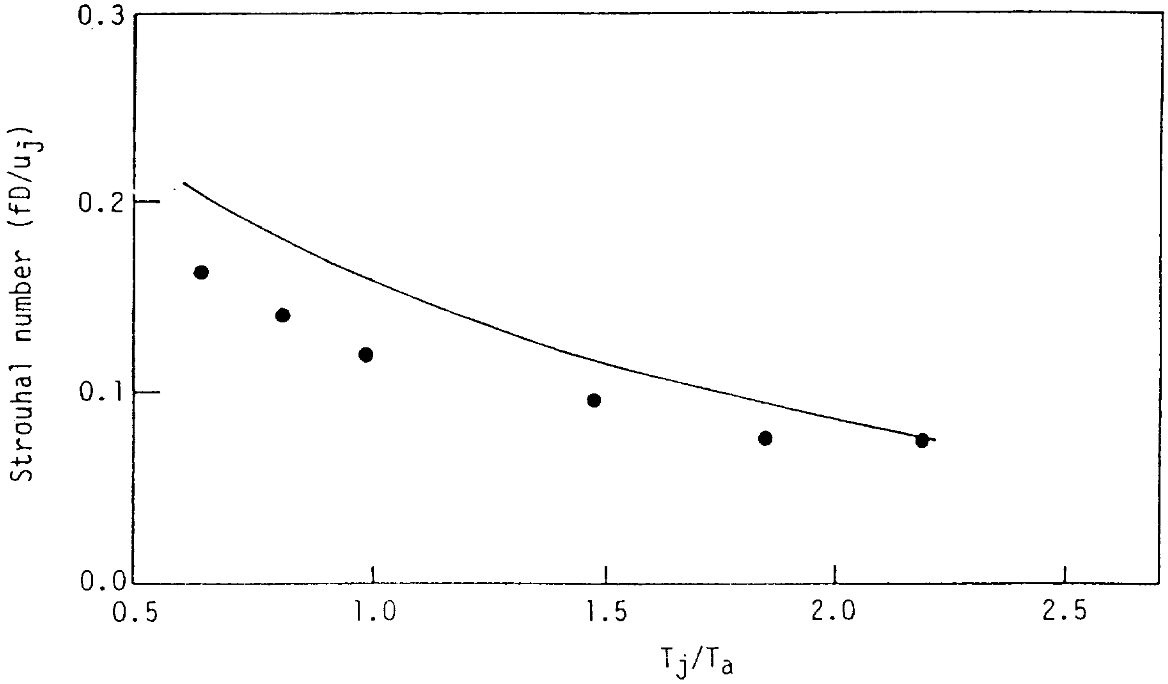
COMPARISONS BETWEEN PREDICTED PEAK NOISE FREQUENCY AND DIRECTION OF RADIATION WITH MEASUREMENTS

If indeed the dominant part of turbulent mixing noise is generated by Mach wave radiation associated with the instability waves then the dominant noise frequency of a perfectly expanded supersonic jet must be nearly equal to that of the most amplified instability waves. Further the direction of peak noise radiation must be equal to the Mach wave radiation angle of the most amplified instability wave. Extensive comparisons between the calculated (theoretical) and measured peak frequencies and directions of radiation for jets of different Mach number and total temperature have been carried out in ref. [5]. Good agreements are found (see figure below).



Comparison of the frequency and direction of Mach wave radiation of the most amplified instability wave of a Mach 2 jet at a total temperature of 855°F. Shown are contours of equal sound-pressure-level in the θ-frequency plane. ● theoretical value.

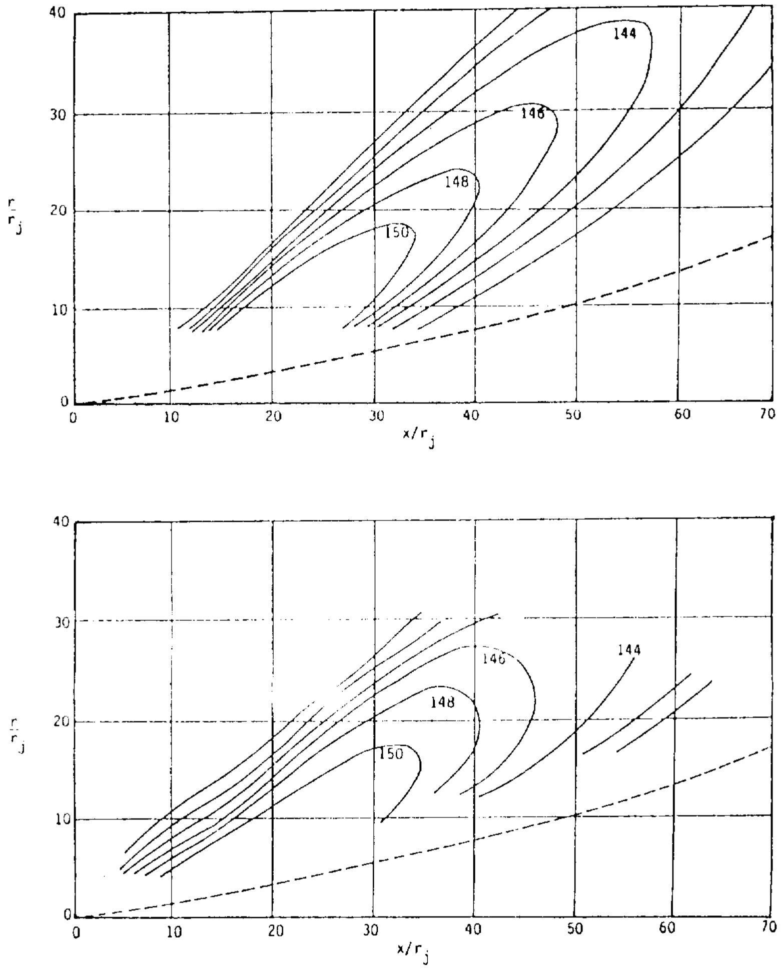
For slightly supersonic cold jets the instability waves would propagate downstream with subsonic velocity relative to the ambient speed of sound. In this case a direct wavy wall analogy would produce no sound. In order to determine the noise generated by the large scale subsonic instability waves their spatial growth and decay in the flow direction must be taken into account. It can be easily shown that with wave amplitude variation even a subsonic instability wave would have some supersonic wave components [4]. These components will radiate noise. However, the radiation efficiency is not high and decreases rapidly with a decrease in wave propagation speed. a comparison between the calculated frequency of the most amplified instability wave and that of peak noise radiation (see figure below) shows good agreement at high jet temperature or high jet velocity. The good agreement deteriorates as the jet temperature and velocity decrease (the wave speed becomes subsonic) consistent with the above reasoning.



The Strouhal number at maximum sound-pressure-level of a Mach 1.7 jet as a function of jet to ambient temperature ratio. ——— theory; ● experiment.

NEAR FIELD SOUND PRESSURE LEVEL CONTOURS

The instability wave theory for a single frequency wave is well established [4]. The theory can calculate the near field pressure contour (relative) distribution as well as the far field directivity at a given Strouhal number. A typical calculated near field pressure contour distribution is given below. It compares very favorably with measurements. A comprehensive turbulent mixing noise theory capable of predicting the entire noise spectrum is still unavailable at the present time.

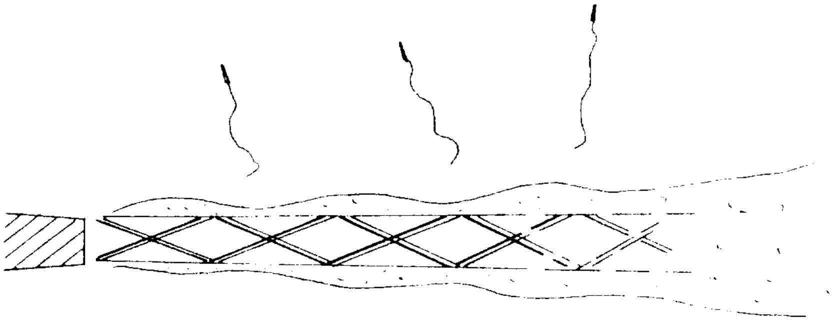


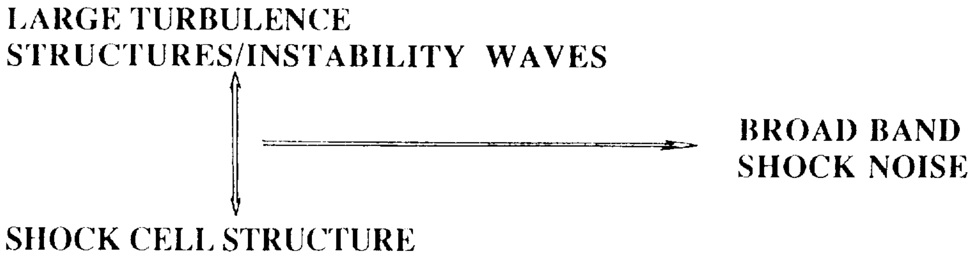
Near field sound-pressure-level contours ; $M_j = 2$, St = 0.38
Calculated (top) , measured (bottom)

GENERATION OF BROADBAND SHOCK ASSOCIATED NOISE

Broadband shock associated noise is generated by the weak interaction between the large turbulence structures/instability waves and the quasi-periodic shock cell structure as the former propagate through the latter. One simple way to see this is to consider a single instability wave. As this instability wave passes through the shock cells scattering takes place resulting in acoustic radiation. A very comprehensive stochastic model theory [6], [7] has been developed which can predict the spectra and directivities of this noise component. The theory can also predict the near field noise pattern as well. Recently the theory has been extended to include the effects of forward flight [8]. The predicted results compare very favorably with measurements.

BROADBAND SHOCK ASSOCIATED NOISE





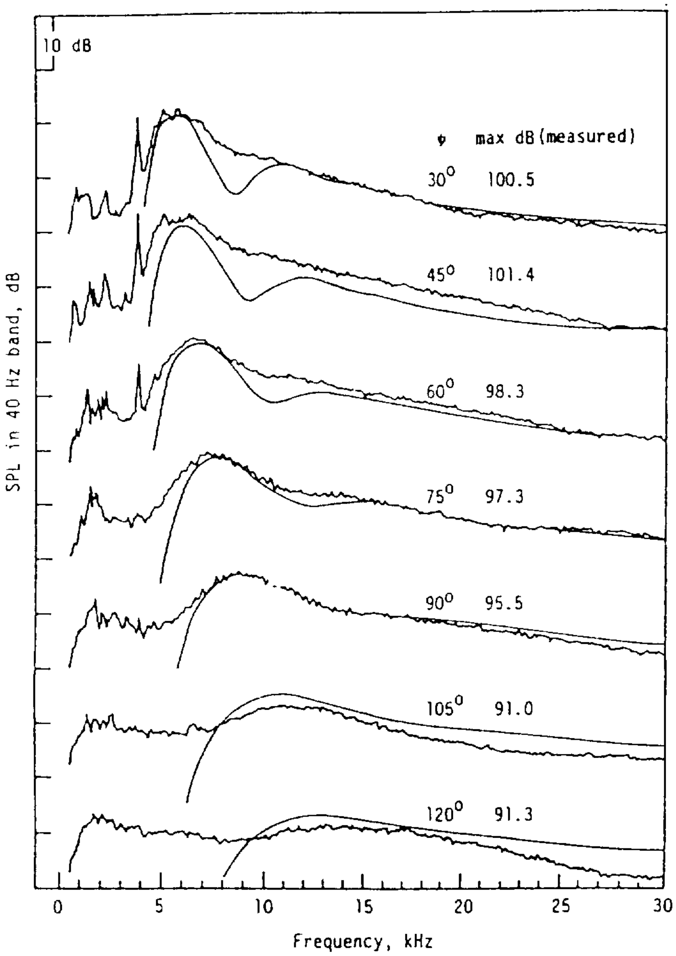
LARGE TURBULENCE
STRUCTURES/INSTABILITY WAVES

BROAD BAND
SHOCK NOISE

SHOCK CELL STRUCTURE

CALCULATED AND MEASURED FAR FIELD SHOCK NOISE SPECTRA

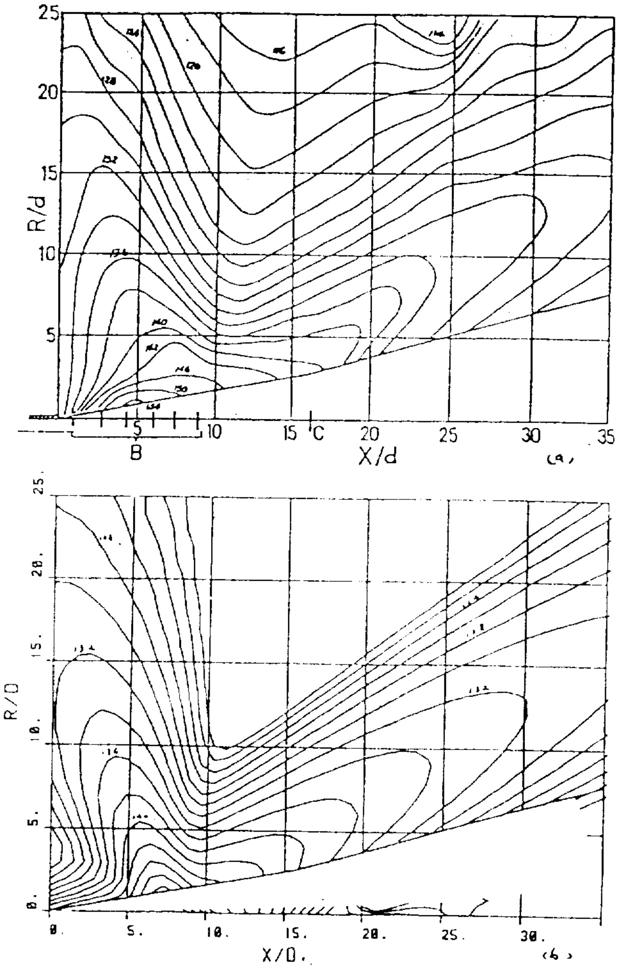
Extensive comparisons between theoretical and measured far field broadband shock associated noise have been carried out [7]. Below is a typical case. The peak frequency of broadband shock associated noise varies with the direction of radiation. The half-width of the spectral peak decreases in the forward direction. These features appear to be quite well predicted by the theory.



Far field noise spectra. $M_d=1.5$, $M_j=1.28$. ∿∿∿, measured
——, calculated

CALCULATED AND MEASURED NEAR FIELD SHOCK NOISE SPL CONTOURS

This is a comparison between the calculated and measured near field noise pressure contours on a plane passing through the jet axis according to the stochastic model theory [6] at a 1/3 octave band center frequency of 16 KHz. A 1.4 dB has been added to the calculated noise contour to give a better comparison with measurements. (The error is of the order of 1.4 dB). The broadband shock noise is represented by the lobe radiating to the left. The dominant direction of noise radiation and the location of the contours appear to be reasonably well predicted.

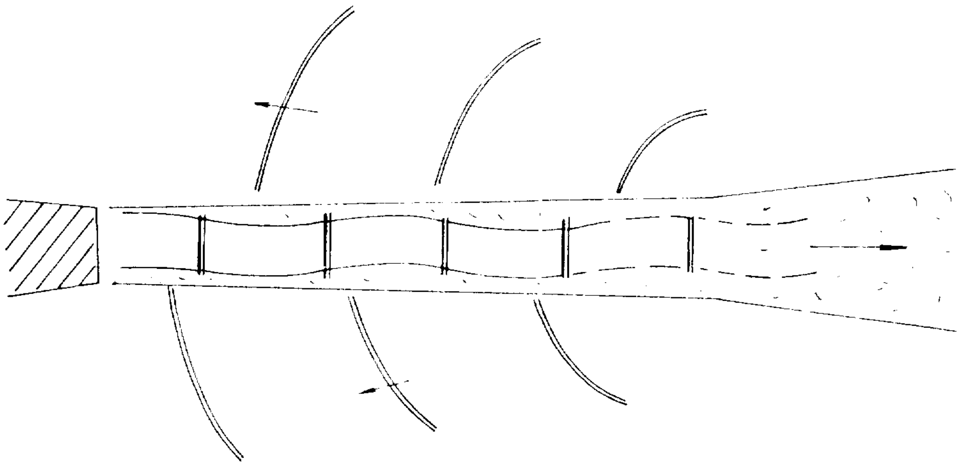


Near-field sound-pressure-level contours.
$M_j = 1.67$, $M_d = 1.5$ (a) Measured ,
(b) Calculated + 1.4 dB. f = 16 KHz

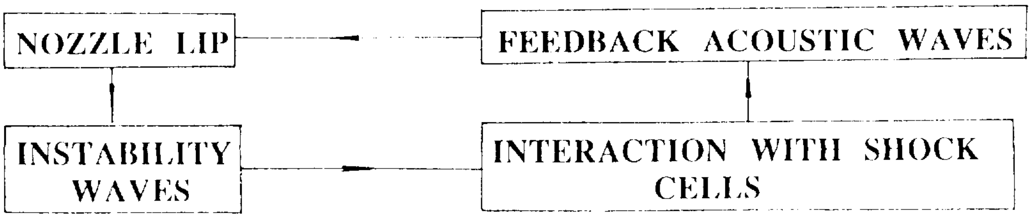
GENERATION OF SCREECH TONES

Screech tones are generated by a feedback loop [9], [10]. Near the nozzle lip the pressure and velocity fluctuations associated with acoustic disturbances outside the jet can excite the Kelvin-Helmholtz instability of the jet. The instability wave extracts energy from the mean flow and grows as it propagates downstream. At about four or five shock cells downstream the amplitude of the instability wave becomes sufficiently large to interact strongly with the shock cell structure. This interaction produces very strong acoustic radiation. A part of the acoustic waves created radiates upstream. Upon reaching the nozzle lip the acoustic waves excite the shear layer of the jet creating new instability waves. In this way the feedback loop is closed.

GENERATION MECHANISM OF SCREECH TONES

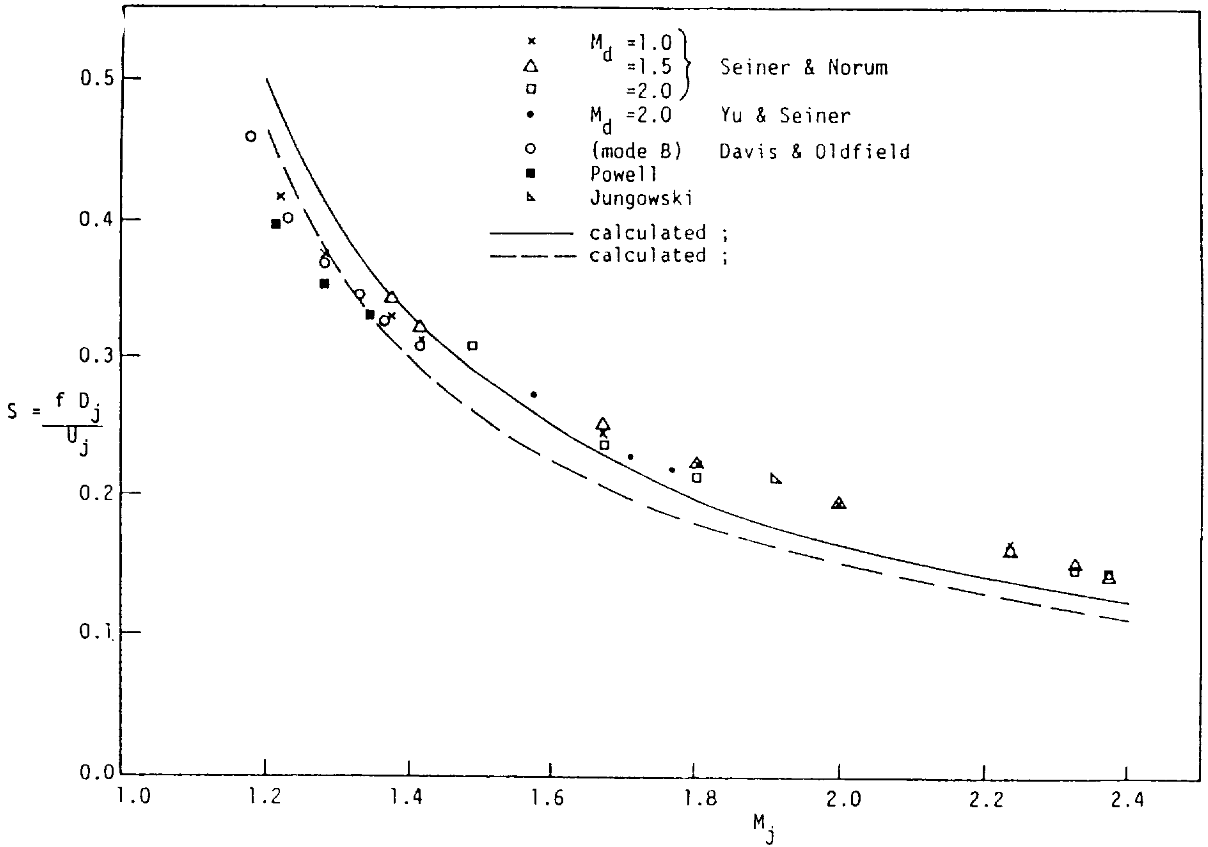


FEEDBACK LOOP



CALCULATED AND MEASURED STROUHAL NUMBER OF SCREECH TONES

By using the feedback loop model it is possible to calculate the Strouhal number of the fundamental screech tone. In this figure the solid curve represents the calculated frequency [10] as a function of jet Mach number. The dotted curve represents a simplified prediction using a simple empirical formula for the propagation speed of the instability wave. Screech tone amplitudes are very sensitive to the presence or absence of reflecting surfaces in the near environment. Sometimes it is difficult to reproduce the same screech amplitude even in the same experimental facility. Perhaps because of this variability there is no screech tone intensity prediction formula at the present time; even a totally empirical one.



The Strouhal number of fundamental stable screech tones versus fully expanded jet Mach number (cold jets).

SUMMARY AND FURUTE WORK

At the present time the generation mechanisms of the three principal noise components of supersonic jets, namely, the turbulent mixing noise, the broadband shock associated noise and the screech tones are quite well understood. A very comprehensive broadband shock associated noise prediction theory for round jets is now available. The theory can predict the far field noise spectra and directivity. A similar comprehensive turbulent mixing noise theory applicable to hot as well as cold jets is still needed. However, the noise directivity at a single frequency can be calculated within the framework of current theory. Work on developing a noise prediction theory for non-axisymmetric jets, such as jets from rectangular nozzles, is under way. A shock noise prediction scheme for non-axisymmetric jets may become available soon. The frequencies of screech tones can be predicted with reasonable accuracy. Because of its sensitivity to the surrounding environment, currently there is no theory capable of predicting the intensity of screech tones.

SUMMARY AND FUTURE WORK

- **NOISE GENERATION MECHANISMS UNDERSTOOD**
- **GENERAL FRAMEWORK OF NOISE PREDICTION THEORY AVAILABLE**
- **COMPREHENSIVE TURBULENT MIXING NOISE THEORY (HOT JETS) NEEDED**
- **NON-AXISYMMERTRIC JET NOISE THEORY NEEDED**
- **SCREECH TONE (INTENSITY) THEORY NEEDED**

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Session V. Sonic Boon (Aerodynamic Performance)

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Session V. Sonic Boom (Aerodynamic Performance)

Sonic Boom Program Overview and Sonic Boom Source Design/Prediction/Performance Overview
Dr. Christine M. Darden, NASA Langley Research Center

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Sonic Boom Program

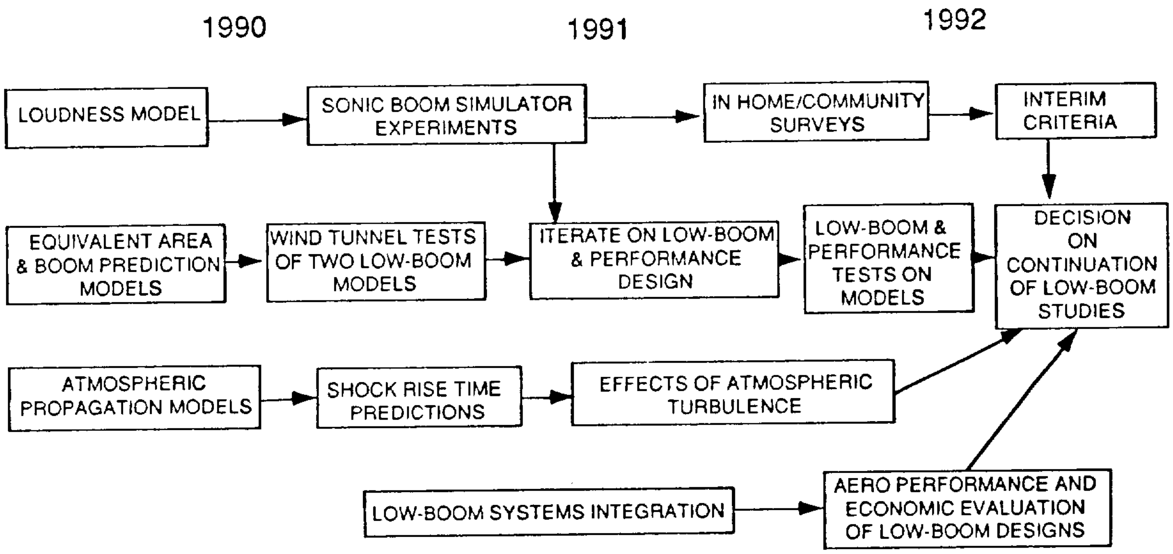
Overview

Christine M. Darden

NASA Langley Research Center

Figure 1

Sonic Boom Research Plan



1990

1991

1992

LOUDNESS MODEL

SONIC BOOM SIMULATOR EXPERIMENTS

IN HOME/COMMUNITY SURVEYS

INTERIM CRITERIA

EQUIVALENT AREA & BOOM PREDICTION MODELS

WIND TUNNEL TESTS OF TWO LOW-BOOM MODELS

ITERATE ON LOW-BOOM & PERFORMANCE DESIGN

LOW-BOOM & PERFORMANCE TESTS ON MODELS

DECISION ON CONTINUATION OF LOW-BOOM STUDIES

ATMOSPHERIC PROPAGATION MODELS

SHOCK RISE TIME PREDICTIONS

EFFECTS OF ATMOSPHERIC TURBULENCE

LOW-BOOM SYSTEMS INTEGRATION

AERO PERFORMANCE AND ECONOMIC EVALUATION OF LOW-BOOM DESIGNS

Figure 2

Sonic Boom Decision Criteria

- A low-boom configuration design comparable to an unconstrained design in terms of economic viability
  - system studies to determine trade-off between performance penalties and economic benefit of overland supersonic flight
- Low-boom design methodology validated by wind tunnel tests
  - configuration designs and models by LaRC, ARC, Boeing and DAC
- Estimate of acceptable sonic boom exposure
  - Dose-response relationship from laboratory and in-home studies
- Estimate of sonic boom levels from a low-boom configuration in a realistic atmosphere
  - Analytical modelling to include atmospheric turbulence

Figure 2

Sonic Boom Plan Beyond Decision

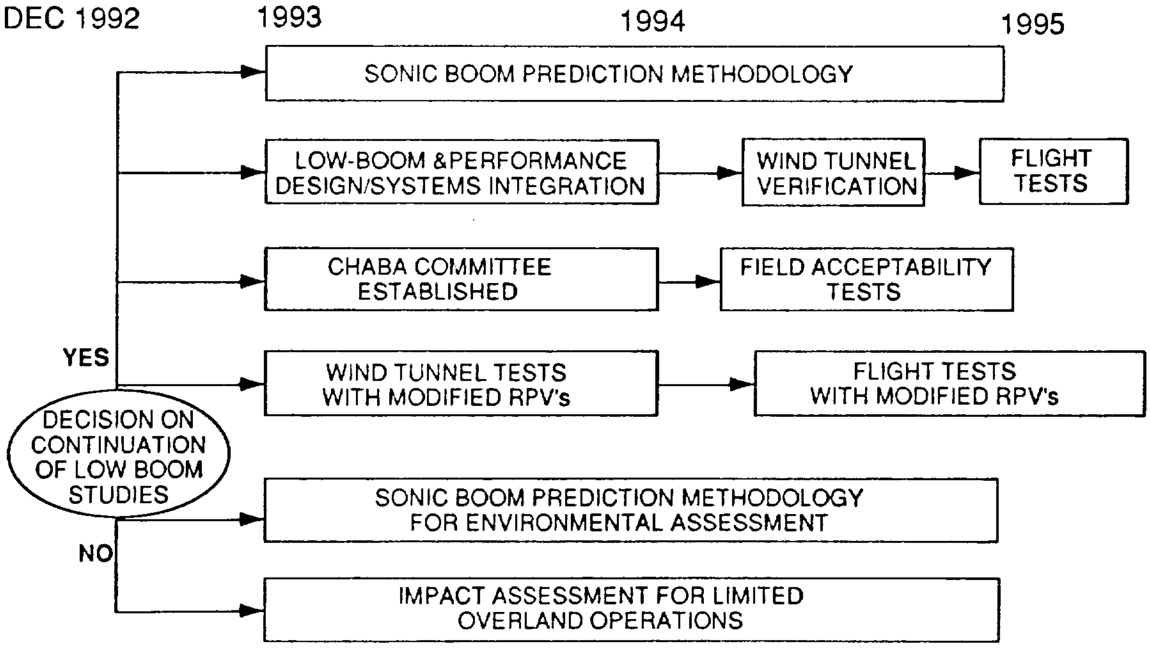

DEC 1992
1993
1994
1995
SONIC BOOM PREDICTION METHODOLOGY
LOW-BOOM &PERFORMANCE DESIGN/SYSTEMS INTEGRATION
WIND TUNNEL VERIFICATION
FLIGHT TESTS
CHABA COMMITTEE ESTABLISHED
FIELD ACCEPTABILITY TESTS
YES
WIND TUNNEL TESTS WITH MODIFIED RPV's
FLIGHT TESTS WITH MODIFIED RPV's
DECISION ON CONTINUATION OF LOW BOOM STUDIES
SONIC BOOM PREDICTION METHODOLOGY FOR ENVIRONMENTAL ASSESSMENT
NO
IMPACT ASSESSMENT FOR LIMITED OVERLAND OPERATIONS

Figure 3

Sonic Boom Issues for Overwater Operations

- Supersonic operations near coastlines
  - during acceleration and deceleration (focused and secondary booms)
  - during cruise (primary boom carpet width, secondary booms)
  - requires prediction of boom levels and location, and audibility criteria

- Incidental overland supersonic operations or restricted corridors
  - environmental impact assessment
  - requires prediction of boom levels and location
  - estimated community reaction, damage probability, etc.

Figure 4

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Sonic Boom
Source Design / Prediction / Performance

Overview

Christine M. Darden
NASA Langley Research Center

Figure 1

Program Elements

Configuration Design
Sonic Boom Analysis - Modified Linear Theory
Performance Analysis
Wind Tunnel Evaluation
Sonic Boom Analysis - Higher Order Methods

Figure 2

Program Participants

NASA LANGLEY
- Vehicle Integration Branch
- Computational Aerodynamics Branch

NASA AMES
- Advanced Aerodynamics Concepts Branch
- Applied Computational Fluids Branch

BOEING COMMERCIAL AIRPLANES
DOUGLAS AIRPLANE COMPANY
GRUMMAN CORPORATION
EAGLE ENGINEERING

Figure 3

Session V. Sonic Boom (Aerodynamic Performance)

Design and Analysis of Low Boom Concepts at Langley Research Center
Dr. Christine M. Darden, Robert J. Mack, Kathy E. Needleman, Daniel G. Baize, Peter G. Coen, Raymond L. Barger, N. Duane Melson, Mary S. Adams, Elwood W. Shields and Marvin E. McGraw, Jr., NASA Langley Research Center

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