RESEARCH IN AERO-ACOUSTICS AT THE ISVR

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1. INTRODUCTION

Research in turbofan aero-acoustics at the ISVR is reviewed in this article with particular reference to a selection of projects which are currently under investigation within the Rolls-Royce University Technology Centre (UTC) for Gas Turbine Noise. This was established at the ISVR in 1999. It is funded by Rolls-Royce plc with support from the DTI to conduct research on gas turbine noise, principally in application to commercial aircraft engines. The UTC also undertakes related noise research funded by other agencies such as EPSRC and the EU. At present the UTC supports the activities of 18 staff and researchers of whom 7 are funded through EU or EPSRC contracts. In this article, a selective overview is given of the work which is currently in progress within the UTC. No attempt is made to present a comprehensive account of all activities.

The UTC is active in four broad areas of research. These are

- Fan and Turbine noise
- Acoustics of nacelles and liners
- Jet noise
- Advanced measurement techniques

A single project has been selected from each of the above categories for current presentation. These involve the following topics; modelling rotor-alone 'buzz saw' tones, finite/infinite element propagation modelling of turbofan intakes, jet noise, and the application of source location techniques to aircraft gas turbine noise.

2. FAN AND TURBINE NOISE. BUZZ SAW TONES

Aircraft engines operating with fan tip speeds which exceed the speed of sound are known to generate an acoustic signature containing energy spread over a wide range of harmonics of the engine shaft rotation frequency (known as Engine Order harmonics or EO's). Commonly referred to as "Multiple Pure", "Combination" or "Buzz-saw" tones, this noise source has been a prevalent feature of aircraft noise since the entry into service in the 1970's of higher bypass ratio aircraft engines.

"Buzz-saw" noise is particularly apparent during take-off and climb, and affects both the cabin and community noise levels. This noise source remains a current concern with the advent of larger aircraft engines, the likelihood of more stringent noise regulations and a public demand for lower aircraft noise levels.

Research reported during the 1970's (see Newby [2.1]) offered a reasonable explanation of the basic generation and controlling mechanisms of this noise in terms of a high-amplitude irregular sawtooth pressure signature within the inlet duct. A simple plane two-dimensional model of the "rotor-alone" pressure field, with supersonic flow impinging on the fan rotor blades, is shown in Figure 2.1. The Mach numbers of the approach flow and fan blade tips are M_a and M_t respectively. This results in a flow impinging on the rotor blades with relative Mach number M_{rel}. For $M_{rel} > 1$ the pressure field consists of a series of shock- and expansion-waves. The pressure signature in a direction normal to the shock fronts will resemble a sawtooth waveform.

The pressure signature associated with an ideal fan, consisting of precisely identical rotor blades in a uniform flow, will be a regular sawtooth. The frequency spectrum of a regular sawtooth only contains energy at the Blade Passing Frequency (BPF) harmonics. All the shocks will propagate upstream of the fan at the speed of sound c_0 relative to the oncoming fluid (weak-shock theory). Therefore the blade-to-blade periodicity in the pressure signature will be maintained. High-pitched tonal noise will be generated because the energy remains confined to the BPF harmonics.

In practice the rotor blades will not be precisely identical; there will be small variations between the blades' profiles, spacings and stagger angles. In [2.1] it was shown that initial variations in shock strength (in the pressure sawtooth) are attributable to stagger angle variations of $O(0.1°)$. Therefore in practice the pressure signature will be an irregular sawtooth which contains features that only repeat once per engine revolution. The frequency spectrum of an irregular sawtooth now contains energy distributed amongst all the EO's (not confined to only the BPF harmonics).

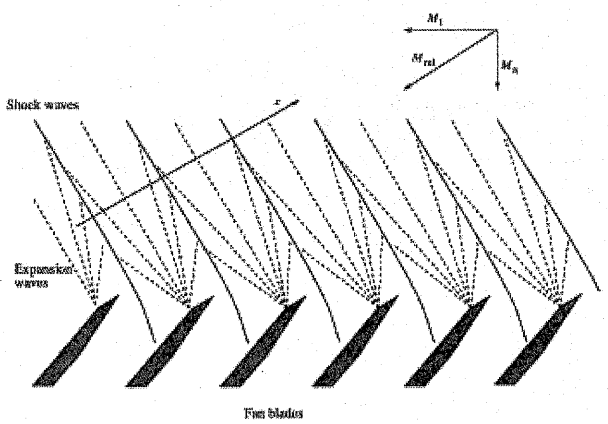

Figure 2.1: Shock-wave generation by a supersonic fan

The shocks in an irregular sawtooth will propagate upstream of the fan at slightly different speeds (relative to each other). Therefore the shocks in the sawtooth will become increasingly non-uniformly spaced. Commonly the blade-to-blade periodicity observed in the pressure signature near the fan will be lost, and by the end of the inlet duct the dominant energy will now be at EO harmonics whose frequencies are less than BPF. The redistribution of acoustic energy between the EO harmonics occurs during the nonlinear propagation of a high-amplitude irregular sawtooth. Therefore a lower-pitched more "ragged" noise will be generated because of the presence of energy in the low-frequency EO harmonics. This is known as the "Buzz-saw" signature of a supersonic rotor. A comparison of the pressure signature and the EO ("Buzz-saw") frequency spectrum at the fan- and inlet-planes inside an inlet duct is shown in Figure 2.2.

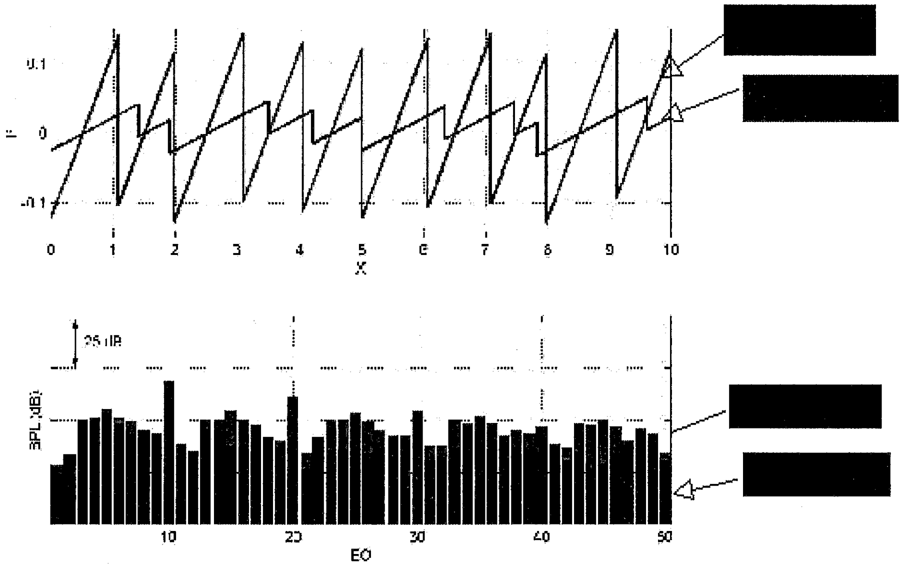

Figure 2.1: Example illustrating the nonlinear propagation of an irregular sawtooth pressure waveform in an inlet duct. (a) Comparison of the pressure signature at the fan-plane and the inlet-plane. (b) Comparison of the EO frequency spectrum at the fan-plane and the inlet-plane. Note that this is a simple example for a 10-bladed rotor.

The plane two-dimensional model of the "rotor-alone" pressure field does not include the inlet duct. In order to include the effect of "cut-off" in a rigid inlet or liner attenuation in a lined inlet it is necessary to transform the problem into the modal/frequency domain because "cut-off" and liner attenuation are determined by mode number and frequency. This may not easily be incorporated into the time domain.

Following the initial work by Fisher, Tester and Schwaller [2.2], McAlpine and Fisher [2.3-2.5] have developed a numerical prediction model "FDNS" (Frequency Domain Numerical Solution) for calculating the nonlinear attenuation of tones in an inlet duct. In a lined inlet duct there will be attenuation resulting from nonlinear interactions between the EO harmonics and due to the acoustic lining on the duct walls. The "FDNS" method includes both of these effects, and for a given pressure signature generated by a supersonic ducted fan, the resultant EO ("Buzz-saw") frequency spectrum in the inlet duct may be predicted. (Then, in principle, the far-field "Buzz-saw" noise spectrum may be calculated by using a suitable radiation model.) Full details of the "FDNS" method are in [2.3-2.5]. The noise radiated from the inlet duct of an aero-engine may not be confined to the "Buzz-saw" noise. In practice, the inlet flow will not be uniform and "scattered" tones will be generated, (closely analogous to rotor-stator interaction tones). Also acoustic liners will contain several "hard" splices aligned axially on the inlet duct wall. These splices will also lead to the generation of other "scattered" tones. In a rigid inlet duct it is believed that the dominant tonal noise source (at supersonic fan operating speeds) will be "Buzz-saw" noise. However in a lined duct the "Buzz-saw" tones may be well attenuated by the lining and it is questionable whether these tones will remain the dominant noise source at all the supersonic fan operating speeds.

3. NACELLES AND LINERS. FINITE AND INFINITE ELEMENT MODELS

3.1 INTRODUCTION

Large reductions have been achieved in the noise radiated by turbo-fan aircraft engines over the last forty years. A significant portion of the reduction can be attributed to the introduction of the turbofan bypass stream in the late 1960s. This reduced jet noise dramatically, a benefit that became more pronounced as the by-pass ratio increased in successive generations of aero-engine. A steady but less dramatic contribution to overall noise reduction has resulted from the development of more effective acoustic treatments for inlet and bypass ducts. This work has proceeded over the last three decades and continues to the present. It forms an important component of the EU SILENCE(R) programme in which the UTC has a significant involvement. Much of this centres on being able to simulate the effect of potentially beneficial novel acoustic treatments for turbo-fan inlets, such as zero-splice liners and barrel liners which extend past the throat of the nacelle. The UTC seeks to develop numerical techniques which can deal with such problems. Currently, a coupled Finite Element (FE)/Infinite Element (IE) code ACTRAN is being used to model the inlet duct and the surrounding region. The method is based on a velocity potential representation for the acoustic field and includes the effects of refraction by the mean flow [3.1]. Work is also in hand within the UTC to extend this approach to the time domain [3.2] where the resulting models lend themselves more readily to parallel computation, an important consideration when fully three dimensional inlets are considered.

3.2 BENCHMARKING FE/IE COMPUTATIONS FOR INLET ACOUSTICS

FE/IE models have been used for flow acoustics for some years but little has been presented by way of validating these codes, particularly for the case when flow is present. A useful test problem for which an analytic solution is available and which incorporates many of the characteristics which must be modelled in a turbofan inlet is indicated in figure 3.1(b). This shows an unflanged duct in a uniform mean flow. The analogy with the inlet region of a turbofan engine is indicated in figure 3.1(a). An exact solution exists for the unflanged duct when a prescribed radial mode is incident at the fan plane [3.3] . Figure 3.1(c) shows a Finite Element mesh which has been used to model the pipe and its near field. The far field region is modelled by a mesh of infinite elements – not shown in figure 3.1 - which are compatibly matched to the inner mesh at its outer boundary. A comparison of computed and analytic far-field directivities is shown in figure 3.1(d). The inlet Mach number in this case is 0.5, the reduced frequency is 40 (i.e $ka = 40$, where k is the acoustic wavenumber and a the radius of the inlet) and the azimuthal spinning mode number is *30*. These correspond to realistic values for a blade passing, rotor-alone tone in a modern turbofan aero-engine operating at a relatively high power setting. Comparisons with analytic results are shown for the first three radial modes which have cut-on ratios of 1.41, 1.19 and 1.07 respectively. Results such as these confirm the accuracy of this approach certainly for uniform mean flows.

3.2 APPLICATION TO NON-UNIFORM FLOWS

In real aero-engine inlets, the mean flow is not uniform. Indeed it can contain large variations in subsonic Mach Number particularly at take-off and landing when noise considerations are critical. The effect of such variations is similar to that of inhomogeneous material properties on disturbances propagating in a stationary acoustical medium. That is to say, the wavelength λ of a harmonic disturbance propagating against a mean flow of Mach number M is related to the wavelength λ_0 of the same disturbance propagating in fluid at rest by the relationship

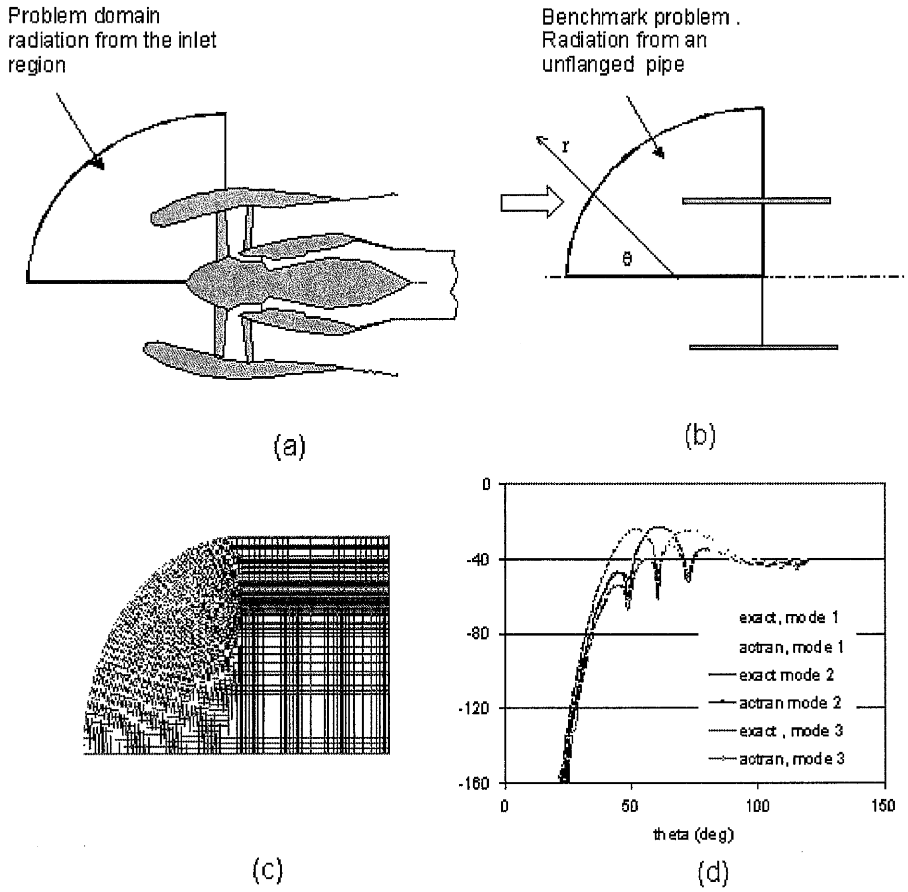

Fig 3.1 . A benchmark problem for inlet radiation

$$\lambda = \frac{\lambda_0}{1-M}$$

This has a pronounced effect on the acoustical field within the inlet at high power settings when the Mach number can vary from approximately 0.5 on the fan plane to 0.9 or higher close to the lip, leading to a fivefold compression of the local wavelength along the inner surface of the nacelle. This is illustrated in Figure 3.2 (a) which shows an inlet mesh which has been constructed for a realistic inlet lip geometry for such a condition. The mesh has been generated by assuming a uniform density of approximately ten nodal points per axial plane wavelength throughout the solution domain. Regions of high nodal density therefore correspond to local regions of high Mach number. Instantaneous contours of acoustic velocity potential within the inlet are shown in figure 3.2(b) for a typical solution obtained for this mesh. The first radial mode is incident at the fan plane and the inlet is lined with a single cavity liner characteristic of those to be found in a modern turbofan inlet. The attenuation of the acoustic disturbance as it propagates along the inlet is clearly visible as is the compression of the local wavelength due to the high Mach number near the throat and the creeping diffraction of the acoustic field due to the finite curvature of the lip. These are all significant determinants of far field directivity and fly-by noise. Solutions of this type are currently being used to optimise the extent and impedance of inlet liners to achieve reduced far field noise levels.

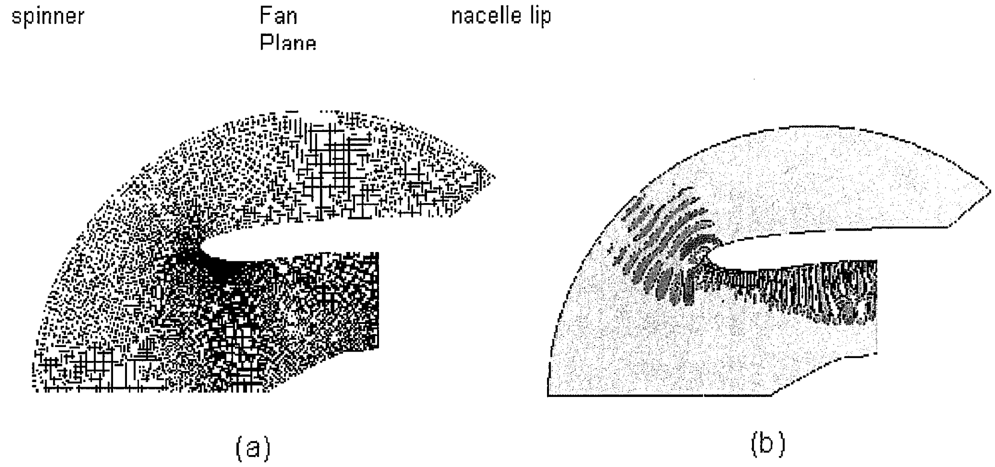

Figure 3.2 . FE Mesh and pure tone solution (m_ϕ=26, n_r=1, freq. 1.5kHz) for a realistic inlet geometry. Mach number at the fan plane ~ 0.5, Mach number in the far field ~0.25.

4. JET NOISE

4.1 INTRODUCTION

The current programme of jet noise research at the ISVR is concentrated, as one would expect, on the noise of coaxial jet flows typical of the modern generation of High Bypass Ratio engines; the Rolls-Royce TRENT family is a typical example. The foundation for the present work was laid during the late 1990's. An empirical, but physically based, model for co-axial jet noise was developed based on a systematic database provided by QinetiQ (Pyestock). Now termed the 'Four Source Model', this work has been fully reported in [4.1], [4.2].

The first subsequent development is directed towards an extension of this 'Four Source Model' to the prediction of near field pressures generated by simple coaxial jet flows. Funded by the EPSRC, with additional support from Airbus (UK), this on-going work is described in section 4.2 below.

The second development is of a somewhat more fundamental nature and involves a close collaboration with Loughborough University (J McQuirk and G Page). A clear limitation of the Four Source Model is the requirement for turbulence input data; obtained originally from the measurements of Ko [4.3] for a simple coplanar jet configuration. Thus, while the model successfully predicts variations of noise created by changes of velocity, velocity ratio and temperature, it fails on changes of nozzle geometry unless the mean and turbulent flow fields are available. The objective of this programme, also funded by the EPSRC, is to obtain this flow field information using efficient, affordable RANS CFD for input into a more advanced aeroacoustic prediction model capable of calculating the noise output from successive axial slices of the jet flow. The development of the latter, for which the ISVR is responsible, is reviewed in section 4.3 below.

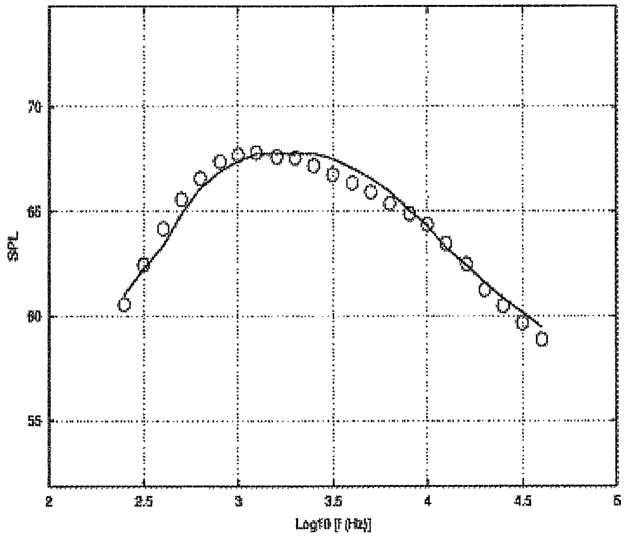

Figure 4.1: Comparison of four source model prediction (solid curve) with measured data (circles). Primary jet conditions: Diameter: 0.0333m, Temperature: 577.2K, Velocity: 210.5 m/s. Secondary jet conditions: Diameter: 0.0745m, Temperature: 278.9K, Velocity: 168.55 m/s.

4.2 NEAR FIELD NOISE PREDICTION FOR COAXIAL JETS

The essential features required for the prediction of noise spectra in the near field of a jet flow are the strengths, directivity and axial location of the contributing sources. The former two are provided by the four source model, but the details of the latter were of no great significance for far field noise prediction.

To overcome this problem a comprehensive set of source location measurements were undertaken in March 2001. Conducted in the NNTF at Pyestock these tests involved:

- 3 area ratios
- 3 velocity ratios
- 3 primary jet temperatures

covering a total of 66 test points. The source location microphone array contained 40 microphones and a total of some 20 Gbytes of data were acquired. Additional far field data was also acquired and analysed by QinetiQ staff. A distinct benefit of this latter data was the opportunity to re-benchmark the four source model against an independent dataset. A typical comparison, see figure 4.1, shows good agreement between data and prediction.

Development of the majority of the source location algorithms has also been completed and an example of an axial source strength distribution for a coaxial jet is shown in figure 4.2. Clearly visible at these conditions are two contributing regions. The one closest to the nozzle is the interaction region where the primary and secondary flows combine followed by a second contribution due to the fully mixed flow. The relative contributions of these two sources shows good agreement with the predictions of the four source model. One aspect of our current work is aimed at the automatic separation of two such sources, particularly for lower frequencies where they are less well resolved.

4.3 A CFD COUPLED APPROACH TO JET NOISE MODELLING

As mentioned in the introduction a limitation of all jet noise prediction models which rely on turbulence scaling laws arises when nozzle geometries are altered. The coaxial jet configuration in which a host of geometric arrangements are in common use, (i.e. variations of area ratio, ¾ cowl, common nozzle assemblies to mention but three) is particularly difficult in this respect. This problem is partially overcome if the changes of flow field properties can be predicted using an affordable CFD solution. Such a solution was identified in the RANS CFD programmes available at Loughborough University.

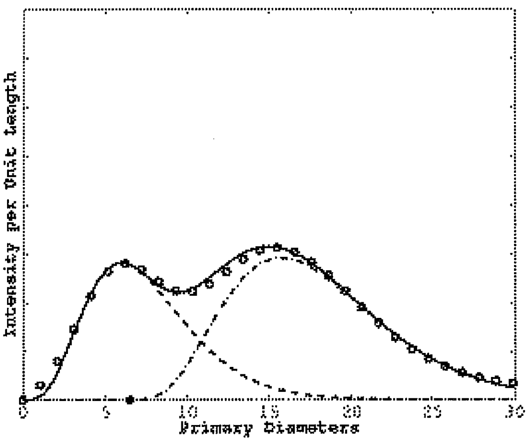

Figure 4. 2: Using the source location algorithm the measured axial source strength distribution (circles) can be fitted using two sources. The individual sources are shown as dashed curves and their sum is the solid curve.

The second half of the problem may then be identified as that of developing a robust aeroacoustics noise prediction model in which the available flow field information constitutes the input.

One suggestion for such an approach as been proposed by Tam [4.4]. However Tam's approach to a source term is somewhat non standard while his form of cross spectral function for the turbulence is adopted by assertion; not from measurement per se.

At the outset of the ISVR work therefore the decision was taken to adopt a source term from the Lighthill analogy and to recognise from the outset that the fundamental source term was a stress fluctuation; *not* a velocity fluctuation. It was indeed fortunate that relevant data on stress fluctuation characteristics for a single jet had been published by Harperbourne [4.5] in 1999.

The three fundamental inputs required to calculate the noise output of a given axial slice of jet flow are mean velocity profiles, turbulence profiles and the cross spectral function. The latter incorporates two pieces of information; the spectrum of the turbulence and the rate at which the turbulence loses its coherence as it convects downstream. The latter is measured through what is termed the moving axis length (or time) scale. Initial attempts to predict jet noise spectra resulted in predicted spectra which were significantly narrower than those measured; similar results were reported from the USA.

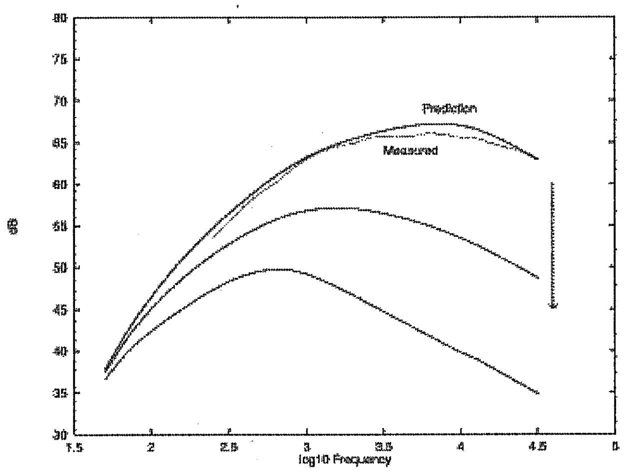

Figure 4.3: Predicted (solid lines) and measured (dotted line) spectra for a single jet. The upper curve uses the variation of moving axial length scale as in [5] and the arrow indicates increasing range of frequency over which it is held constant.

Subsequent investigation has shown clearly that this is the result of the common assumption in jet noise modelling that the moving axis length scale (see above) is independent of frequency. Experimental data, due to Fisher [4.6], published in the 1960's demonstrated that this was not the case. The timescale is constant over a range of low frequencies, but then diminishes as the inverse of frequency. The results in [4.5] show a similar behaviour. The effect is demonstrated in figure 4.3. The upper predicted spectra, showing good agreement with data, is based around the variation of moving axis length scale reported in [4.5]. The lower curves show the effect of assuming a constant moving axis length scale over successively increased ranges of frequency. The result is as expected when one remembers that, for subsonic jet velocities, the turbulence only produces noise due to changes of turbulent structure; a frozen pattern is silent.

Finally in this context the astute reader will already have observed that source distributions of the type discussed in Section 2.0 are obtained a welcome intermediate stage of the calculations described in this section. These have been calculated and also show good agreement with measurement for the single jet flows considered to date.

5. MEASUREMENT TECHNIQUES. THE APPLICATION OF SOURCE LOCATION TECHNIQUES TO AIRCRAFT GAS TURBINE NOISE

5.1 INTRODUCTION

The assessment of the effectiveness of noise control measures applied to aircraft gas turbines may be assisted by a detailed knowledge of the position and strength of the various noise sources. The current work is concerned with investigating the application of various source location algorithms to the output signals of a 2-dimensional floor-mounted microphone array positioned close to an engine.

5.2 STRATEGY

Investigations into the number and position of the microphones in the array are carried out via computer simulations of the array outputs in response to a variety of source distributions. These signals are then processed using various source location algorithms to attempt to reconstruct the (known) source distributions.

The simulations allow the performance of the different algorithms to be compared in terms of the accuracy of source reconstruction, computational effort etc. The validity of the computer simulations is checked by applying the algorithms to real data recorded from a microphone array mounted in the large anechoic chamber at ISVR. Further tests on a model fan are planned.

5.3 THE FOCUSSED BEAMFORMER

One of the simplest source location algorithms is the focussed beamformer. The output signals from the microphones are summed after passing through a set of filters designed so that the microphone array is focussed on a point in space where a source is expected to be. The optimum filter set is related to the vector of Green functions linking the source to the pressures at the microphones. As the beamformer algorithm is quite efficient, it is possible to use it to 'scan' an area or volume of space to find sources whose position is unknown. Figure 5.2 shows a simulation of the result of scanning a 2m by 2m plane containing a single monopole source. The microphone array consists of 64 microphones arranged in a spiral pattern covering an area of 4.5m by 4.5m. The relative positions of the source plane and array are shown in Figure 5.1.

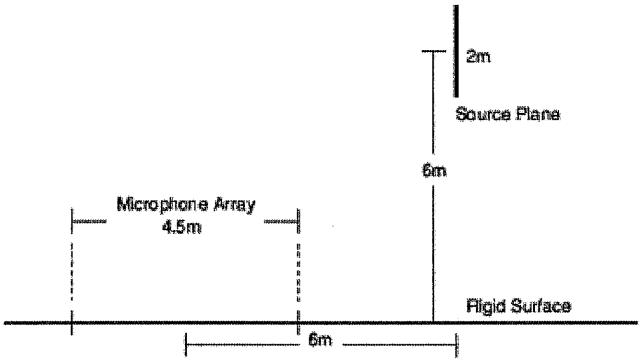

Figure 5.1 Geometry of Simulation

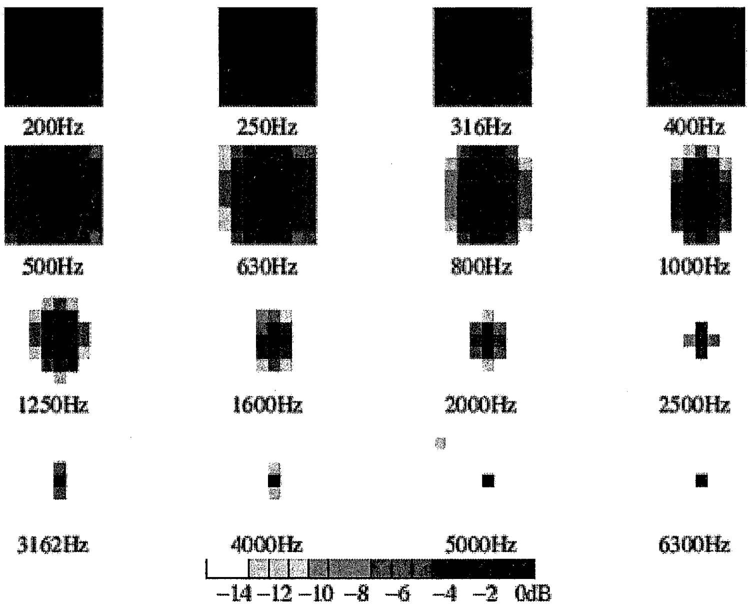

Figure 5.2 Simulation of Scanning a Beamformer over a Source Plane

The beamformer algorithm is shown to work well when only one source is present, but when more than one source exists it gives rise to errors in the estimate of the strengths of the sources. The presence of this error is also evident from the 'real' data recorded in the anechoic chamber. Figure 5.3 shows the error in the estimation of source strength of one of four mutually incoherent sources spaced 0.5m apart; both the simulated and actual errors are presented.

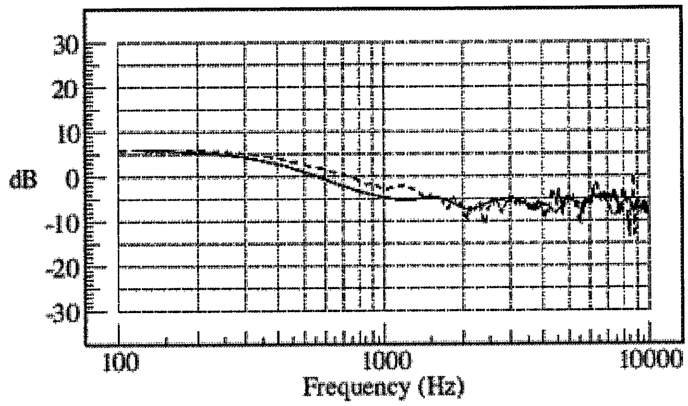

Figure 5.3 Error in Source Strength Estimation of one of four incoherent sources: simulation, solid line: real data, dashed line.

5.4 THE INVERSE METHOD

The multiple source problems encountered with the beamformer can be overcome by employing inverse techniques. These algorithms involve the inversion of a matrix of Green functions which, along with a matrix of microphone pressure cross spectra, yields the optimum estimate of a matrix of source cross spectra. The inverse method can be applied to any number of sources up to a maximum equal to the number of microphones in the array, but the Green function matrix is ill-conditioned if there are many sources close together. Applying the inverse method to the four source simulation above gave rise to an error-free reconstruction of all four sources.

6. ACKNOWLEDGEMENTS

The research outlined in the preceding sections gives a representative but necessarily incomplete account of Aero-Acoustic research at the ISVR. The work presented here has been funded by Rolls Royce plc, the Department of Trade and Industry, the EC (through projects JEAN, RESOUND, and SILENCE(R)) and EPSRC (grant GRM/79509)

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