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JET ENGINE NOISE SOURCE BREAKDOWN

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I. Introduction

The total noise field of a modern high by-pass ratio aero-engine can usefully be considered as made up of noise radiating from the inlet duct, bypass duct, hot core exhaust and from a distributed source of jet mixing noise downstream of the nozzles. An accurate estimate of the contribution made by each of these sources, the so-called "source breakdown," is of vital importance to the engine manufacturer for a number of reasons. First the merit of applying acoustic or other treatment to a portion of the engine, with its associated weight or other penalties, must be viewed in the context of the net noise reduction achieved. Secondly the static-to-flight behaviour of engine based sources is different to that of the jet mixing noise, so that translation of static-to-flight data requires a source breakdown. Finally accurate prediction methods for each source are required to guide optimum cycle changes for "stretched" versions of existing engines.

An awareness of the potential importance of this data led Rolls-Royce to initiate an investigation of methods for its measurement other than via relatively expensive "Quiet Engine Demonstrator" programmes; the goal being the experimental determination of source breakdowns on a non-interference basis during standard noise tests. The outcome of this work was the development of the "Acoustic Telescope" at Cambridge University |1| and the "Polar Correlation Technique" at Southampton University |2|. Both techniques employ an array of far-field microphones and differ principally in the method used to process the data to yield the so-called "source image."

The purpose of this paper is to outline briefly some of the practical problems associated with obtaining source breakdowns via the source image approach and then to describe an alternative method of processing Polar Correlation data which avoids the majority of these difficulties.

II Difficulties Associated with Source Images

A schematic source array for an engine typical of the RB 211 is shown in Fig.1 together with a typical microphone array. Considerable care is necessary in the design of these arrays if correct and useful data is to be obtained. As discussed in detail by Glegg |3|, to avoid aliasing requires a microphone separation given by $\sin(\Lambda) \leq \lambda_2/L$ where λ_2 is the minimum acoustic wavelength of interest and L is total length of the source distribution. Conversely to resolve two sources of separation ℓ requires a total aperture of the array α_m, to be in accordance with $\sin \alpha_m \geq \lambda_1/\ell$ where λ_1 is the maximum acoustic wavelength of interest. Combining these requirements leads to an expression for the number of microphones required; namely

$$N - 1 = \frac{L}{\ell}\frac{f_2}{f_1}$$

where f_2 and f_1 are respectively the highest and lowest frequency of interest. For a typical RB 211 application $\frac{L}{\ell} \sim 10$ (see Figs.2 for actual dimensions) leading to a requirement for about eighty microphones to cover the frequency range 0.5 - 4 kHz.

The use of an equally spaced array of microphones is thus impractical and this has led to the design of 'special' arrays. The first of these was the graded array |3|, while a more recent alternative is the 'course-fine' array. Here 'fine' spacing is used only over a limited portion of the array, but the resolution of the total aperture is obtained by assuming that the cross spectrum is a function only of microphone separation and independent of the reference microphone position. While these designs do reduce the number of microphones to more manageable proportions it is still not uncommon for the frequency range to be limited by available microphone channels. There is also a range of frequencies, below about 0.5 kHz at RB 211 scale, for which the acoustic wavelength is longer than the separation of adjacent sources and sources cannot be resolved irrespective of array aperture.

The nature of these problems is demonstrated in Figs. 2a) to 2d) which show source distributions which would be obtained for an RB 211 if the four sources each contributed equally to the far field noise at frequencies of 1500, 600, 300 and 150 Hz respectively. The microphone array assumed here has a 30^{o} aperture and contains thirty equally spaced microphones.

Fig.2a) demonstrates the high frequency situation for which the sources are well-resolved. To obtain the required source breakdown now requires integration of each portion of the source image; the hatched portion of this figure corresponding to the contribution of the intake source. While not difficult at this degree of resolution the process is nevertheless very time consuming when a large volume of data is to be processed.

At the medium frequency of 600 Hz, Fig.2b), while the presence of all four sources is still clearly apparent, it is also clear that images are beginning to overlap and some degree of judgement will be required to separate their individual contributions. The progressive worsening of this situation at the lower frequencies of 300 and 150 Hz is shown in Figs.2c) and 2d) respectively. It is also relevant to point out that with the microphone array specified the aliasing length at 2,000 Hz is of order 10 meters so that significant aliasing of the intake source onto the jet noise and vice versa will be apparent at this frequency.

We can summarize the major problems of obtaining source breakdown via source images, therefore, as the following:

a) A large, often prohibitive, number of microphones are required to obtain source images over the required frequency range if both adequate resolution and freedom from aliases are to be achieved.
b) A range of lower frequencies exist for which adequate resolution cannot be achieved.
c) Even in frequency range for which good quality source images are available integration of these images to obtain a source breakdown is time consuming.

III The Automated Source Breakdown Technique

An awareness of the problems outlined above prompted a search for alternative methods by which the required source breakdowns might be obtained from the cross spectral data generated by polar correlation measurements. The clue was, in fact, that no use was being made in the standard analysis routines of the known positions of the 'point' sources and the general shape of the mixing noise distribution.

We shall demonstrate how these facts may be beneficially employed in terms of a distribution of three point sources located at y_i

$$S_i(y,\omega) = A_i(\omega)\delta(y-y_i),\ i=1,2,3 \tag{1a}$$

and a distributed source of the form suggested by Glegg |3|

$$S_4(y,\omega) = A_4(\omega)\left\{\frac{(m/Y_4)^m}{(m-1)!}\right\} y^{m-1}\exp(-my/Y_4) \tag{1b}$$

where Y_4 is the centroid of the distributed source and $A_i(\omega)$ is the strength of each source.

The formal relationship between the cross spectral measurements of the polar correlation technique |2| and an arbitrary source distribution of strength S(y) per unit length is

$$C(\alpha,\omega) = \int_{-\infty}^{\infty} S(y,\omega)\exp(-j\omega y\sin\alpha/a_o)dy \tag{2}$$

which for the present model can be written

$$C(\alpha,\omega) = \sum_{i=1}^{3} A_i(\omega)\ \exp(-\frac{j\omega y_i}{a_o}\sin\alpha) + \frac{A_4}{(1+\frac{j\omega}{a_o}\frac{Y_4}{m}\sin\alpha)^m} \tag{3}$$

Clearly, if the measured data, $C(\alpha,\omega)$, were error free and the positions of the sources precisely known then four measurements of the cross spectrum would suffice to solve the set of four simultaneous equations represented by Eq.(3) for the source amplitudes $A_i, i=1,4$. However, in practice the cross spectrum is subject to statistical errors and some small uncertainty exists about the precise positions of the sources.

To overcome this problem, instead of obtaining a forced fit to a restricted number of data points as suggested above, a method of least square fitting is employed. That is one chooses positions for the three point sources and the parameters Y_4 and m for the mixing noise source. A least squares fit to the measured cross spectra then results in a simple matrix equation which can be inverted and solved for the source amplitudes.

The particular merits of this procedure are first that the intermediate stage of using a source image prior to the source breakdown is eliminated so that human intervention is avoided; that is the system can be completely automated. Secondly as we shall now proceed to demonstrate accurate source breakdowns are possible at frequencies well below those for which individual sources are resolved by the source image procedure.

IV The Numerical Test Procedure

Before utilising the technique outlined above with real data a numerical simulation study was undertaken. In essence this comprised the following steps:-

a) Specify a set of 'true' source amplitudes and positions.
b) Calculate the 'true' cross spectrum.
c) Add random error of a specified standard deviation.
d) Specify a set of assumed source positions (which will be different from those in (a) when checking the influence of source positioning errors).
e) Perform the 'least squares' fit and derive a set of source amplitudes.
f) Compare the 'true' and derived amplitudes.

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A typical set of results are shown in Figures 3a) – 3d) for which an error of standard deviation 0.05 has been superimposed on the true cross spectrum values. This is typical of the values experienced using existing data processing routines.

Shown in these figures are the true cross spectrum (full line), the data values fed to the least squares fit procedure (crosses), and the least squares curve fit of these values (broken line). Also shown at the bottom of each figure are comparison of the true and derived source amplitudes. The agreement obtained in all cases is very acceptable the error on any individual source amplitude being significantly less than 1dB. In particular we would draw the readers attention to Figures 3c) and 3d) where acceptable agreement is obtained in spite of the fact that the corresponding source images, Figures 2c) and 2d) exhibit a complete lack of resolution of the individual sources.

V Conclusions

a) The 'least squares' fit procedure permits the complete automation of source breakdown calculation by eliminating the source image stage of data analysis. Thus, far larger volumes of data can be processed than has previously been possible.
b) Both numerical studies and practical results have shown that component source amplitudes can be measured at frequencies far lower than those for which corresponding source images exhibit adequate resolution.

References

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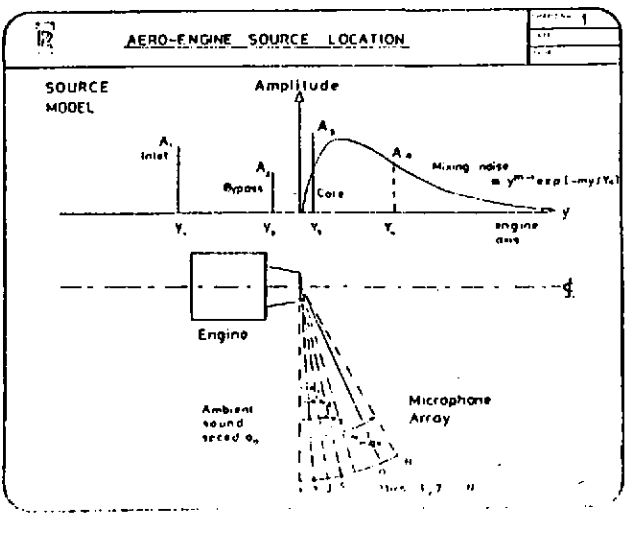
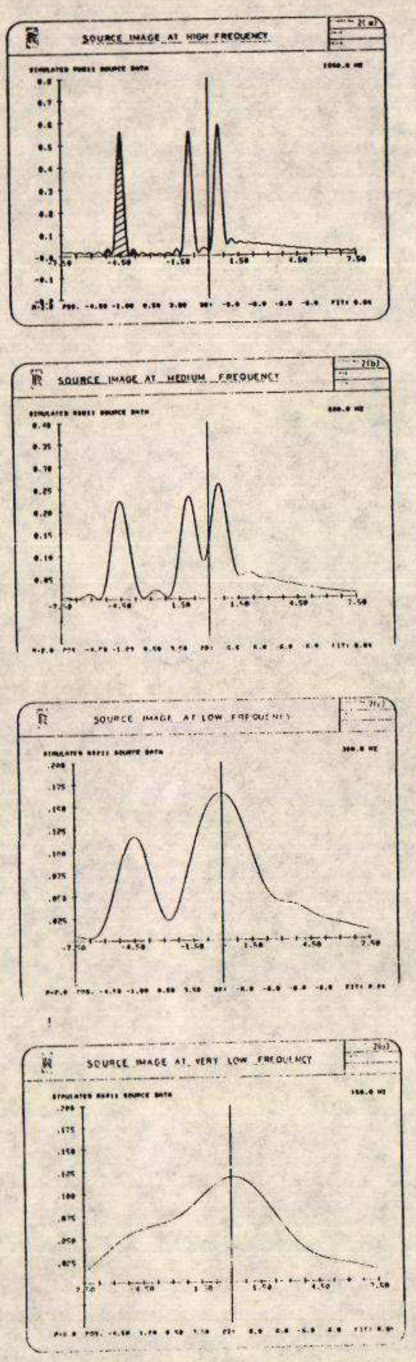
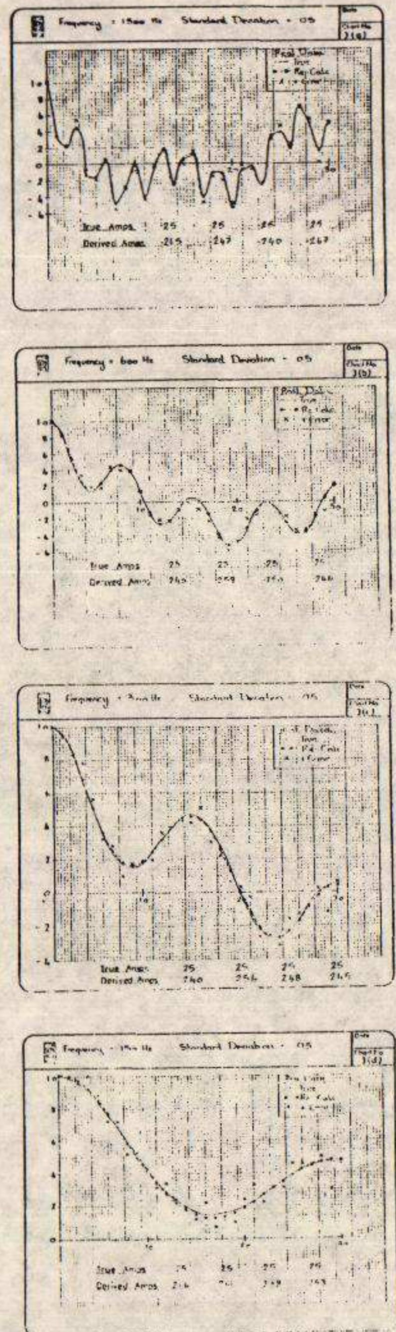
2. M.J. FISHER 1977 J. Sound Vib. 51, 23-54. Jet Engine Noise Source Location: the Polar Correlation Technique.
3. S.A.L. GLEGG 1979 Ph.D. Thesis, University of Southampton. Jet Noise Source Location.




SOURCE IMAGE AT HIGH FREQUENCY
SOURCE IMAGE AT MEDIUM FREQUENCY
2(b)
SOURCE IMAGE AT LOW FREQUENCY
SOURCE IMAGE AT VERY LOW FREQUENCY


Frequency
Standard Deviation
Peak Data
True
Re Calc
True Amps
Derived Amps