High Bypass Ratio Engine Noise Component Separation by Coherence Technique

Belur N. Shivashankara*
The Boeing Commercial Airplane Company, Seattle, Washington

Aft fan, core, and jet noise components of a large high bypass ratio engine (Pratt and Whitney Aircraft JT9D) were separated by the use of a signal enhancement technique. This technique uses simultaneous signals from three or more microphones that are assumed to have a common correlated part and uncorrelated extraneous noise at each location. The main advantages of this technique are 1) internal-to-far-field coherence technique can be used for component separation even when the in-duct microphone signal is contaminated by extraneous noise, as is usually the case, and 2) jet noise can be separated from core plus fan noise by using signals from far-field microphones alone. This paper includes a description of the technique, its validation by controlled model-scale experiments and examples of results from the full-scale engine test.

Introduction

ACCURATE prediction of the various components of aircraft engine noise continues to be an important problem in the commercial airplane industry. Improvements in prediction methods require accurate separation of components from measured total engine noise data.

Separation of a component from total engine noise is relatively simple for dominant components such as fan tones at the blade passage frequency. Often two or more components with competing levels and similar spectral shapes add up to give the total noise. Under such circumstances, it becomes extremely difficult to accurately separate the components. However, even components that are significantly below total noise need to be accurately predicted. Since they 1) form noise floors that limit the benefits to be gained by reducing other dominant components, and 2) may become important in flight when components such as jet noise are reduced owing to relative velocity effects.

To improve the accuracy of component separation and source isolation beyond that possible from conventional methods, the cross-correlation and coherence function techniques can be used. In principle, these techniques are capable of separating components even when they are several decibels, say 10-20 dB, below the total noise. The level of success in achieving this depends on several factors such as 1) the ability to instrument the test engine at the required locations, 2) the extent to which the assumptions relating to the technique are valid for the given environment, and 3) frequency response and dynamic range of data acquisition and reduction equipment, etc.

Internal-to-far-field coherence function analysis was used in Refs. 1-4 to isolate the sources of gas turbine engine core noise. In all these references very interesting and valuable information was obtained regarding source mechanisms and source locations. In Refs. 1-3, the authors used ordinary coherence function (explained in the next section) between internal and far-field microphones and, then, derived the far-field core noise component by calculating the coherent output power. The coherent output power will give the core noise component, if the assumption of a linear system can be made and, the induct microphone is free from extraneous noise. However, any microphone mounted in a flow duct measures a signal that is not only due to the propagating noise but also due to local boundary-layer fluctuations. The boundary-layer fluctuations (also called hydrodynamic noise) that do not propagate contaminate the measured internal signal. Thus the coherent output power in the far field is usually lower than the true core noise. So far the problem has been that one did not have a measure of the signal to noise for the internal signal. This is not a problem when the coherence between induct and far-field microphone signals is near unity. The high coherence assures that there is high signal-to-noise ratio at the internal location and also that the far-field signal is dominated by core noise.

More often, the core noise is not the only important source in the far field because other sources such as jet noise may also contribute substantially. Under such circumstances the internal-to-far-field coherence will be appreciably lower than unity. Although this situation happens to be the one which is of most interest, the ordinary coherence result becomes impossible to interpret without any knowledge of the degree of internal microphone signal contamination due to extraneous noise. The low coherence could be either due to the contamination of the induct signal or due to core noise not being dominant in the far field. So far the problem has been the lack of knowledge of the signal-to-noise ratio at the induct location.

In this paper, it is shown that this difficulty is overcome by using a method based on the technique for rejecting flow noise published by Chung.[5] This method, which will be referred to as the signal enhancement technique, uses simultaneous signals from at least three microphones. These signals are analyzed for coherence in pairs. The assumption (in addition to those for coherence function analysis) are 1) the microphones selected all receive the signal that is of interest, and 2) the extraneous noise at the microphones is uncorrelated. The method is described in this paper. Also, results from a proof-of-concept model-scale laboratory test are included to illustrate the validity of the method. Recently, Krejsa[6] has presented a paper where he used a three-signal coherence technique. Krejsa's technique is essentially the same as that of Chung[5] although the mathematical derivations are different.

A Pratt and Whitney JT9D engine was tested with four dynamic pressure transducers in each of the fan and core ducts. In this paper, the engine test is described and results obtained by the use of the signal enhancement technique to separate the core, fan and jet noise components are presented. Signals from two core nozzle microphones were used along with a far-field microphone signal to derive the core noise component in the far field without the effect of extraneous noise. Similarly, the fan noise component was derived by

Presented as Paper 81-2054 at the AIAA 7th Aeroacoustics Conference, Palo Alto, Calif., Oct. 5-7, 1981; submitted Oct. 14, 1981; revision received May 13, 1982.

*Senior Specialist Engineer.

using two fan duct signals with that from a far-field microphone.

Also presented in this paper are results for the separation of the sum of core plus fan noise from jet noise using far-field microphones alone. For this, the signals from three widely separated far-field microphones were used along with the concept suggested by Parthasarthy et al.[7] that jet noise is not correlated between two far-field microphones that are separated by a large angle.

Analysis Method

Coherence Function

The analysis uses the coherence function calculated between pairs of microphone signals. Detailed discussions of the coherence function can be found in textbooks such as Ref. 8. Let us consider a single input/single output system where $x(t)$ is the input, $y(t)$ is the output, and $H(f)$ is the frequency response function. The spectra for $x(t)$ and $y(t)$ are, respectively, $G_x(f)$ and $G_y(f)$. $G_{xy}(f)$ is the cross power spectrum between $x(t)$ and $y(t)$. If $G_x(f)$ and $G_y(f)$ are both different from zero and do not contain delta functions, then the coherence function between the $x(t)$ and $y(t)$ is a real valued function defined by

$$\gamma_{xy}^2(f) = |G_{xy}(f)|^2 / G_x(f) G_y(f) \tag{1}$$

From the above equation it can be shown that for all f,

$$0 \leq \gamma_{xy}^2(f) \leq 1 \tag{2}$$

For the ideal case of a constant parameter linear system with a single clearly defined input and output, the coherence function will be unity. If $x(t)$ and $y(t)$ are completely unrelated, the coherence function will be zero. If the coherence function is finite but less than unity, one or more of three possible situations exist[8]: 1) extraneous noise is present in the measurements; 2) the system relating $x(t)$ and $y(t)$ is not linear; and 3) $y(t)$ is an output due to $x(t)$ as well as to other inputs.

For a moment, assume that only situation 3 is the reason for coherence being less than unity. Under this assumption, one can calculate the part of the output spectrum $G_y(f)$ which is due to the input $x(t)$ by the relation

$$G_{cy}(f) = \gamma_{xy}^2(f)\, G_y(f) \tag{3}$$

$G_{cy}(f)$ is called the coherent output power.

Now consider the engine noise case. Assume that $x(t)$ is the core nozzle pressure fluctuation and $y(t)$ is the pressure signal at the far-field microphone. If $x(t)$ is considered to be entirely due to core noise and $y(t)$ to be due to core noise as well as jet noise, fan noise, etc., then we can get the core noise spectrum in the far-field by calculating the coherent output power spectrum.

The coherence function approach in an ideal situation would, therefore, enable isolation of the core noise component quantitatively from the far-field spectrum. In most practical situations, however, extraneous noise is present in the induct measurements and the coherent output power does not yield the desired component information. This situation can be overcome by the use of the signal enhancement method developed by Chung[5] for flow noise rejection.

Signal Enhancement Method

The signal enhancement method of Ref. 5 needs simultaneous signals from a minimum of three microphones. The basic assumptions are that 1) the system is linear, 2) all the microphones receive the signal of interest which is perfectly correlated between the microphones, and 3) extraneous noise at each location is completely uncorrelated. Under these assumptions, it becomes possible to separate the correlated part from the extraneous uncorrelated noise at each measurement location.

The analysis method will be presented in this section in a simplified manner. Detailed descriptions and derivations can be found in Ref. 5. Consider first two microphones. The system can be represented by the simplified block diagram shown in Fig. 1. For the present, consider only microphones 1 and 2 and ignore microphone 3. $x(t)$ is the sum of the correlated part $u(t)$ and extraneous noise $l(t)$. Similarly, $y(t)$ is made up of the correlated part $v(t)$ and extraneous noise $m(t)$. Under the assumptions made, the coherence between $u(t)$ and $v(t)$ is 1 and the coherence between $l(t)$ and $m(t)$ is 0.

The coherence function between $x(t)$ and $y(t)$, $\gamma_{xy}^2(f)$ can be shown to be given by (see, e.g., p. 641 of Ref. 9)

$$\gamma_{xy}^2(f) = \gamma_{uv}^2(f) \Big/ \left(1 + \frac{G_l(f)}{G_u(f)} + \frac{G_m(f)}{G_v(f)} + \frac{G_l(f) G_m(f)}{G_u(f) G_v(f)}\right) \tag{4}$$

where the G's denote the respective power spectral densities.

However, $\gamma_{uv}^2(f) = 1$, and let $a = G_l(f)/G_u(f)$ be the noise-to-signal ratio at microphone 1 and $b = G_m(f)/G_v(f)$ be the noise-to-signal ratio at microphone 2.

Equation (1) can be written as

$$\gamma_{xy}^2(f) = 1/(1 + a + b + ab) \tag{5a}$$

or

$$a + b + ab = [1 - \gamma_{xy}^2(f)]/\gamma_{xy}^2(f) \tag{5b}$$

The above equation has two unknowns, a and b, that are of interest. To make the problem determinate, simultaneously recorded signals from a third microphone is added (Fig. 1). And, let the noise-to-signal ratio at the third microphone be c.

By choosing microphones in pairs, we get the following set of equations:

Microphones 1 and 2,

$$a + b + ab = [1 - \gamma_{xy}^2(f)]/\gamma_{xy}^2(f) \tag{6a}$$

Microphones 1 and 3,

$$a + c + ac = [1 - \gamma_{xz}^2(f)]/\gamma_{xz}^2(f) \tag{6b}$$

Microphones 2 and 3,

$$b + c + bc = [1 - \gamma_{yz}^2(f)]/\gamma_{yz}^2(f) \tag{6c}$$

Now we have three equations in three unknowns a, b, and c. The quantities $\gamma_{xy}^2(f)$, $\gamma_{xz}^2(f)$, and $\gamma_{yz}^2(f)$ are easily obtained by using a two-channel Fourier transform signal analyzer.

Since the correlated parts of the total noise at each location are of interest, the above equations can be solved for a, b, and c. Using the definitions for a, b, and c, it can be shown that[5]

$$\begin{aligned} G_u(f) &= G_x(f)\,[\gamma_{xy}(f)\gamma_{xz}(f)]/\gamma_{yz}(f) \\ G_v(f) &= G_y(f)\,[\gamma_{yz}(f)\gamma_{xy}(f)]/\gamma_{xz}(f) \\ G_w(f) &= G_z(f)\,[\gamma_{xz}(f)\gamma_{yz}(f)]/\gamma_{xy}(f) \end{aligned} \tag{7}$$

The left-hand side of Eq. (7) contains the noise-free autospectral density at each of the microphones. The quantities on the right-hand side are measurable and include the extraneous noise. The quantities on the left-hand side have no effect of the extraneous noise. These equations are used in the present paper to separate the engine noise components.

It can be easily seen that the above method can be applied to signals from more than three microphones. In such a case, the

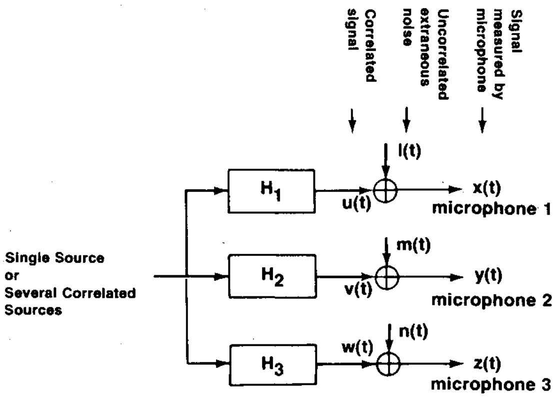

Fig. 1 Schematic diagram of the three microphone arrangement for the signal enhancement technique.

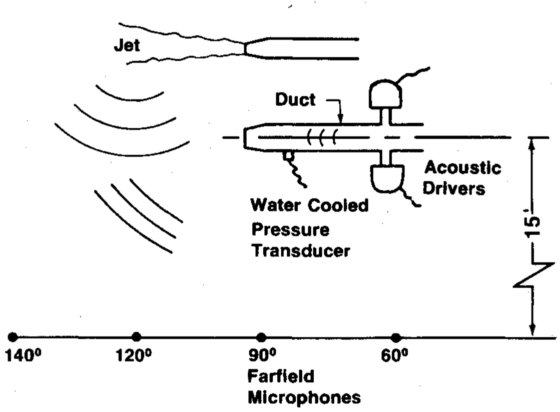

Fig. 2 Schematic of proof-of-concept model test setup.

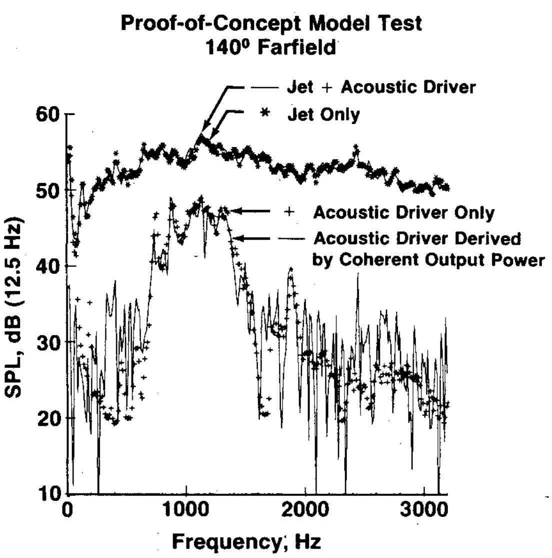

Fig. 3 Comparison of the acoustic driver spectrum derived using in-duct to far-field coherence analysis with that measured directly.

number of equations exceed the number of unknowns and one can derive a least-squares solution.

Proof-of-Concept Test Results

Model Test Description

As mentioned in the Introduction, a proof-of-concept model test was also conducted. A schematic diagram of the test setup in the Boeing Large Anechoic Test Chamber is shown in Fig. 2. Two noise sources were used in this setup. The acoustic driver source was mounted on to the side of a duct and its signal could be monitored by an in-duct pressure transducer of the same type as was used in the core nozzle of the full-scale engine test. A separate jet was used to generate jet noise in the chamber. It was possible to turn on and turn off the noise sources independently of the other sources. As such, the components extracted in the presence of other sources or extraneous noise by the method based on coherence function could be checked against the measurements made with all other sources turned off. The purpose of this test was twofold. First, the test provided end-to-end confidence regarding the instrumentation and the results of the FFT analyzer. Of special concern was the use of an analog tape recorder. The second purpose, of course, was to illustrate the significance of the signal enhancement technique under controlled conditions somewhat similar to an engine noise test situation.

Analysis Using In-Duct and Far-Field Signals

In this section the case where the input signal is relatively free from extraneous noise will be considered. This situation will enable the separation of the signal that is coherent with the input signal by the use of coherent output power calculation [Eq. (3)] and does not need the signal enhancement method. In the next section the case where the input signal is contaminated will be considered.

The model test arrangement is shown schematically in Fig. 2. In this test, first only the acoustic drivers were turned on and both internal and far-field microphone signals were tape recorded. This provided the spectrum due to acoustic driver alone at the far-field location. Next, a jet was turned on in the test chamber to provide masking background noise. With both the jet and acoustic driver turned on together, it was not possible to distinguish the contribution of the acoustic driver by direct visual observation of the far-field spectrum (Fig. 3). The contribution of the acoustic driver to the far-field microphone signal was extracted by computing the coherence function between the in-duct transducer and the 140-deg far-field microphone signals. Since there was no flow in the duct, the in-duct transducer signal could be considered to be free from extraneous noise and as essentially due to the acoustic drivers only. The contribution of the acoustic drivers to the far field obtained by coherent output power calculation [Eq. (3)] is compared with that measured with only the acoustic drivers turned on in Fig. 3. It can be seen that the coherent output power accurately derives the noise due to the acoustic drivers even when it is about 20 dB or more below total noise. Although the result shown in Fig. 3 is somewhat elementary, such an experiment was necessary to establish that the data acquisition and reduction systems were indeed satisfactory and that the assumptions such as linearity, etc., were valid.

Analysis Using Signals from Three Far-Field Microphones

The acoustic data taken during the proof-of-concept test at 60-, 120-, and 140-deg locations were analyzed. As before, the data were taken for 1) acoustic driver only, 2) jet only, and 3) acoustic driver plus jet. For the case with both sources on, each microphone signal is due to the acoustic driver and the jet. If the acoustic driver signal is completely correlated between the three microphones, then it can be considered as the "correlated signal" in the signal enhancement technique. If the jet noise is uncorrelated between the microphones, then jet noise can be looked upon as the uncorrelated extraneous noise at each location. In such a situation, the signal enhancement technique can be used when both sources are turned on to separate the component due to the acoustic driver without the effects of jet noise. The accuracy of the derived component can be checked against that obtained with only the acoustic driver on.

Since three far-field microphones are being used in this exercise, successful separation of the component will also validate the technique of separation of engine noise components using far-field microphones alone. The essential requirement for this will be to show that jet noise is uncorrelated between any two widely separated microphones. Reference 7 postulated that the jet noise will be uncorrelated because of the fact that it is made up of a large number of distributed nonstationary sources. Owing to the different Doppler shifts in different directions, the jet noise will be uncorrelated between microphones that are separated by a large angle.

First, the coherence between the microphones will be examined to determine whether or not the requirements for the signal enhancement technique are satisfied. In Fig. 4, the coherence functions for three separate cases, 1) jet only, 2) acoustic driver only, and 3) acoustic driver plus jet, are presented.

The acoustic driver was excited by a band limited white noise in the frequency region 400-2500 Hz. In this frequency range, it can be seen in Fig. 4 that coherence of nearly unity is obtained for the acoustic-driver-only case. Therefore the acoustic driver's contribution to the total measured signal at the microphones can be considered to be the "correlated signal." For the jet-noise-only case, negligible coherences are seen in the frequency range of interest. Thus jet noise at each location can be looked upon as the uncorrelated-extraneous noise. This also shows that the assumption of Ref. 7 is valid.

The coherence functions obtained for the case when both noise sources were turned on are also shown in Fig. 4. Using these coherence functions and signal enhancement equations presented earlier, the acoustic driver signal at each location was extracted as the correlated part. The jet noise can be obtained as the uncorrelated part by subtracting the correlated part from total noise. The extracted acoustic driver component spectrum is compared with that measured directly in Fig. 5a. Also shown in this figure is the total noise measured when both sources were simultaneously on. The improvement in component separation achieved by the use of the signal enhancement method compared to ordinary coherent power output method using only 60- and 140-deg signals is demonstrated in Fig. 5b. The signal enhancement technique can be seen to be capable of extracting the correlated part even when it is about 10 dB below the total noise. The limitation of 10 dB in most part is due to the dynamic range limitations in the instrumentation and record length limitation, etc. The capability to derive a component that is up to 10 dB below the total noise is very significant in engine noise analysis. Most current methods fail when a component is about 2-3 dB below the total.

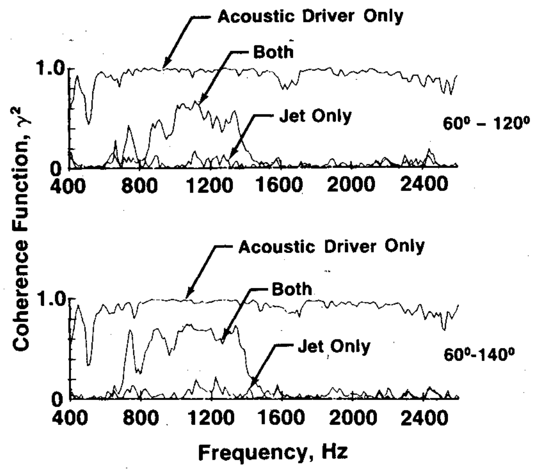

Fig. 4 Coherence function between far-field microphones for different sources.

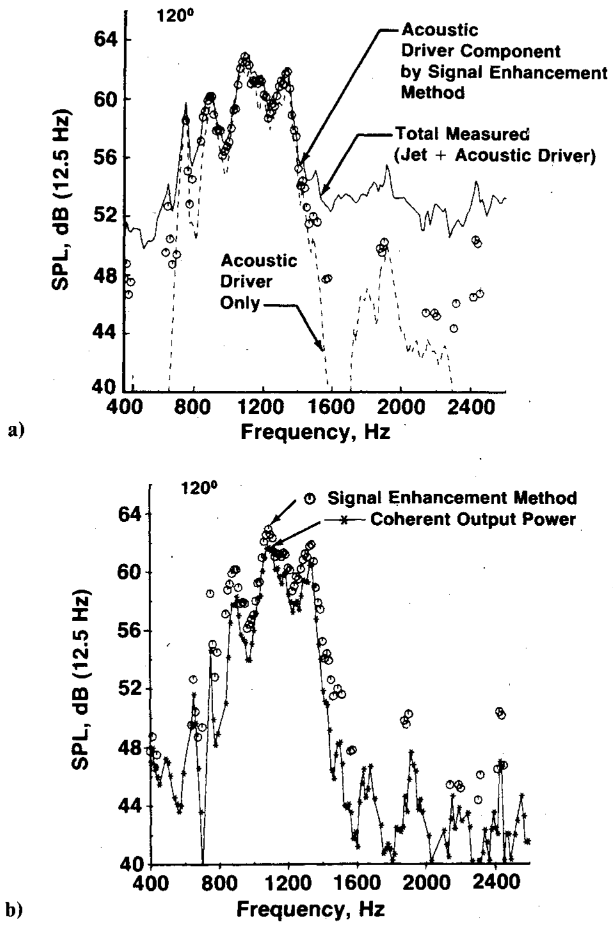

Fig. 5 a) Proof-of-concept test results using 60-, 120-, and 140-deg microphones. b) Acoustic driver component comparisons at 120 deg.

JT9D Test Description

The Pratt and Whitney JT9D engine test was conducted at the Boeing Tulalip Engine Test Facility. The engine was mounted on the monopedestal cantilevered stand at a height of 16 ft above the test pad. The far-field noise measurements were made on a large concrete pad. An inlet flow control structure (ICS) was used to assure low turbulence at the inlet to the engine. The acoustic instrumentation consisted of eight in-duct microphones, two near-field microphones, and several far-field microphones. These are schematically shown in Fig. 6.

The engine noise data were recorded on analog FM tape recorders at a tape speed of 60 in./s for a duration of 3 min. The engine noise data were reduced using a two-channel fast Fourier transform (FFT) analyzer. For all desired pairs of microphones, functions such as the 1) auto spectrum of each channel, 2) cross spectrum, 3) coherence function, and 4) transfer function were calculated. The data reduction was done for five different engine settings that covered idle power to takeoff power. The output of the FFT analyzer was further processed on a minicomputer to separate the components using the signal enhancement technique.

JT9D Engine Test Results and Analysis

Analysis Using Core-Duct and Far-Field Signals

Signals from two of the core nozzle microphones were used with that from one of the far-field microphones at a time to derive the far-field core noise component. By physical reasoning, it was assumed that the spacing between in-duct microphones was sufficient to assure that the extraneous hydrodynamic noise would be uncorrelated between them, although the validity of this assumption could not be proved in the core duct. Similar measurements between two

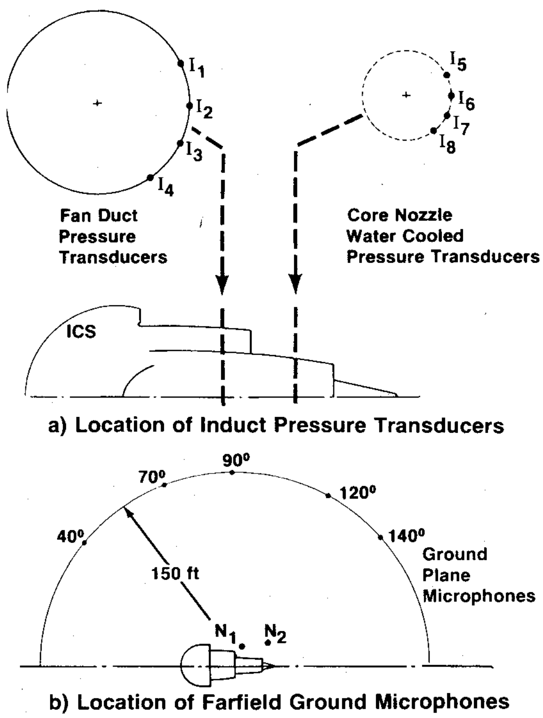

Fig. 6 Instrumentation for JT9D engine static test.

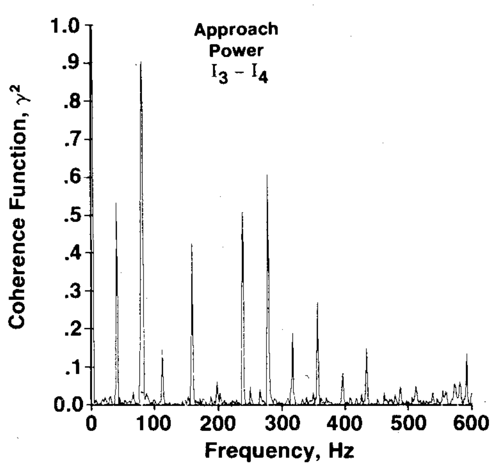

Fig. 7 Coherence between two fan-duct microphones.

microphones in the fan duct could be used as a guide, since the in-duct microphones in the fan duct also experience broadband hydrodynamic noise. The coherence function between two fan duct microphones is examined in Fig. 7. Negligible coherence is obtained for broadband noise, showing that it is reasonable to assume that the hydrodynamic noise is uncorrelated between two fan duct microphones. The same behavior can be expected between two core nozzle microphones also. Core noise was assumed to be perfectly correlated between the three microphone signals being considered.

A typical coherence result between the microphone pairs analyzed is shown in Fig. 8. The engine was operated at an approach power setting. The angle chosen for Fig. 8 is 120 deg, where it is generally expected that core noise is important. There is strong coherence between the in-duct microphone signals at most of the frequencies in the 0-600-Hz range. The internal-to-far-field coherence functions show somewhat lower values and appreciable coherence is seen mostly in the 150-350-Hz range.

The core noise component without the influence of extraneous noise was derived using the signal enhancement

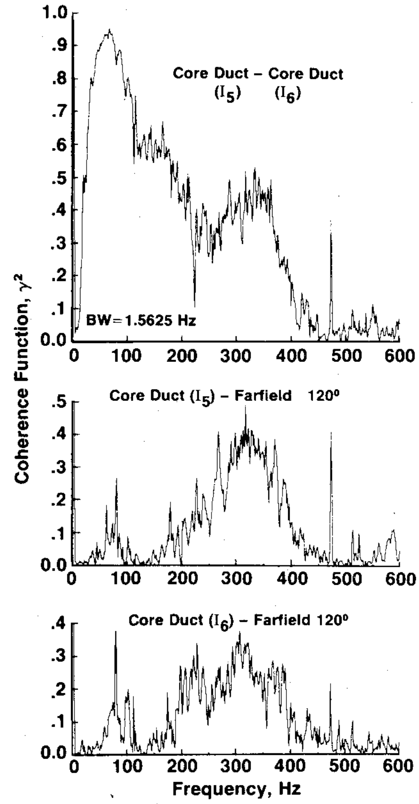

Fig. 8 Coherence functions used in deriving core noise.

method [Eq. (7)] and the coherence functions shown in Fig. 8. For this purpose, all auto- and cross-spectral estimates were smoothed by averaging ten adjacent frequency bands. This was done to reduce the random error at the cost of frequency resolution. The effect of frequency smoothing was to increase the degree of freedom (2 × bandwidth × time) from 250 to 2500. From the examination of a large number of coherence function plots from the test, it was decided that minimum significant value of the coherence function was about 0.05 for the engine noise test. Thus, the derived component at frequencies where the coherence was lower than 0.05 was flagged by the computer program. This was done by artificially assigning a value of total minus 30 dB to the derived component level. From the examination of the engine data and proof-of-concept test results, it was concluded that the components derived by the signal enhancement method could be considered acceptable up to 10 dB below the total noise. Detailed error analysis may enable extension of the dynamic range.

The derived core noise component in the far field is plotted along with measured total noise in Fig. 9. Also shown in Fig. 9, is the core noise estimate that would have been obtained by using ordinary coherence function from one of the in-duct microphones and computing the coherent output power. This coherent output power estimate of core noise is affected by extraneous noise at the in-duct microphone location; therefore it is lower than the estimate obtained by the use of the signal enhancement technique. The spectrum from the signal enhancement technique is a better estimate since it is free from the influence of extraneous noise in the in-duct signal. Similar analysis was done at other power settings of the engine and at various far-field angles.

Analysis Using Fan-Duct and Far-Field Signals

The aft-fan-noise component in the far field was derived in the same way as core noise using two fan-duct microphone signals along with the desired far-field microphone signal. The coherence functions between the microphone pairs for the 120-deg far-field case at approach power, are shown in Fig.

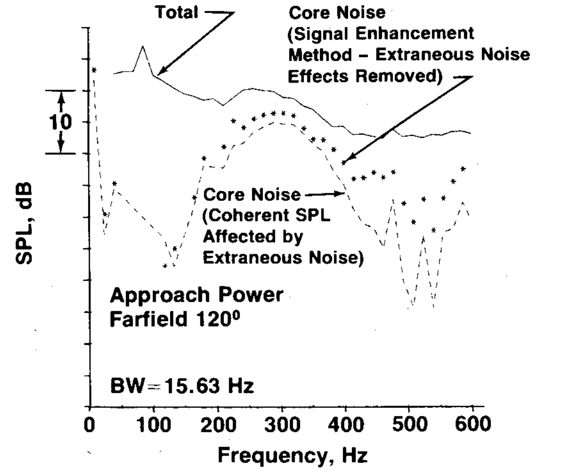

Fig. 9 Core-noise component at 120 deg derived using signals from I5, I6, and 120 deg.

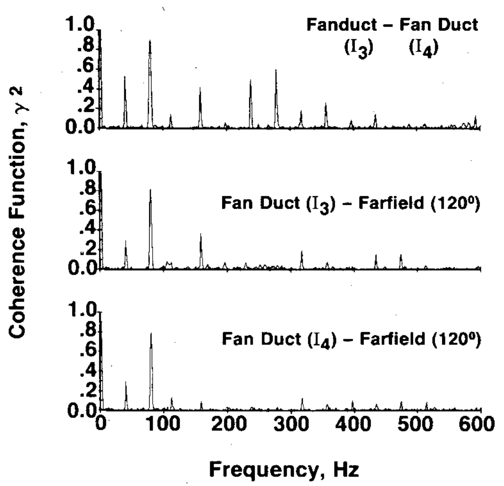

Fig. 10 Coherence functions used in deriving fan noise.

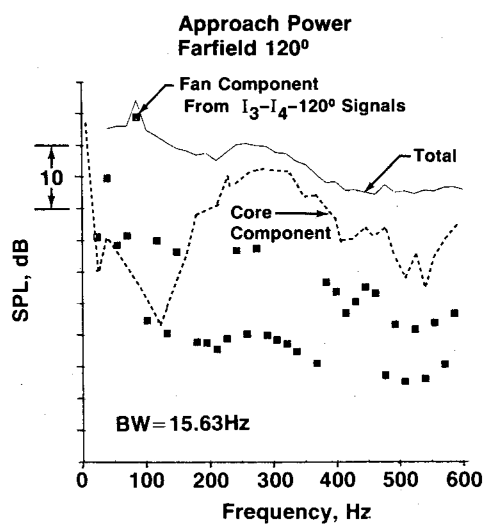

Fig. 11 Full-scale engine fan-noise component by signal enhancement technique, using fan-duct signals.

10. The coherence function between two fan-duct signals can be seen to be near unity at a few discrete frequencies. These frequencies are multiples of the rotational frequency of the low speed spool of the engine. The fan-noise component derived by the use of the signal enhancement technique is shown in Fig. 11. As before, ten adjacent frequency points

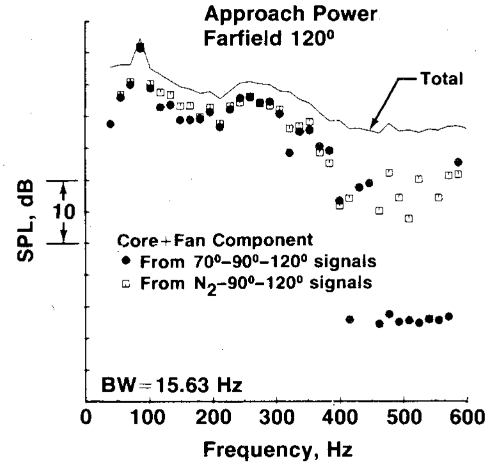

Fig. 12 Component separation using microphone external to the engine.

were smoothed to reduce the random error in the spectral estimates and data with coherence less than 0.05 were considered as insignificant. For reference, the core noise component from Fig. 9 is also shown in dotted lines in this figure. The fan tone is seen at a discrete frequency of about 80 Hz whereas core noise is a broadband noise centered around 250 Hz.

Analysis Using Far-Field Signals Only

In the far field, as mentioned earlier in this paper, the expectation is that both the core- and fan-noise components are perfectly correlated between any two locations external to the engine. The jet noise, on the other hand, because it is due to a large number of distributed-uncorrelated sources, will not be correlated, if the chosen microphones are separated by a large angle. Thus, by proper choice of three far-field microphones, the sum of core plus fan noise can be separated from total noise. By subtracting core plus fan noise from the total noise one would be left with jet noise since in the frequency region being considered the total noise is made up of only jet, core, and fan components. It was shown earlier that these arguments are valid by means of a proof-of-concept model-scale test.

The results of full-scale engine component extraction using signals from far-field microphones at 70, 90, and 120 deg at approach power is presented in Fig. 12. Again, the results are shown at the 120-deg location. It can be seen that the derived correlated part includes 1) the core-noise component in the 300-Hz region that was derived from core nozzle to far-field analysis in Fig. 9, and 2) the fan tone around 80 Hz that was derived by the fan-duct to far-field analysis in Fig. 11. Thus, by the use of far-field microphone signals alone, it has been possible to derive the sum of the core- and fan-noise components.

So far, the discussion has been focused at the use of three far-field microphone signals to derive the correlated part. The same analysis can be done by using signals from, say, a near-field microphone and two far-field microphones. An example of such an analysis is also included in Fig. 12. The estimate for the correlated part at 120 deg using N_2, 90-deg, and 120-deg signals agrees very well with that from 70-, 90-, and 120-deg signals.

Another point to be noted here is that, in the 100-200-Hz region, the correlated part derived using external microphone signals in Fig. 12 is appreciably higher in level than the sum of the individually derived core noise (Fig. 9) and fan noise (Fig. 11). This result indicates that there may be a correlated noise source region external to the nozzles. This region should be either compact or made up of well-correlated sources in order to be well correlated between the widely separated far-field microphones. Detailed study into the nature and cause of this source is beyond the scope of this report. However, it is felt that the correlated external source region may be due to the excitation of the jet by either core- or fan-noise components or both.

Higher Frequencies

At frequencies of 500 Hz and above, fan-duct-to-far-field and far-field-to-far-field analyses showed reasonable coherence at frequencies that were multiples of fan shaft frequency. These included the blade passage frequency (BPF) of the fan and its second and third harmonics.

For the broadband engine noise data, no coherence was observed for all microphone combinations for frequencies greater than approximately 500 Hz. This result was not due to the lack of engine generated broadband noise. The lack of broadband coherence was not an instrumentation problem, because when noise from a loudspeaker in the test arena was used to calculate the coherence between two far-field microphones, a coherence of nearly unity was obtained at the higher frequencies as well.

For a moment, the lack of broadband coherence between two microphones in the far field will be considered. It has already been stated, in this paper, that jet noise will not be correlated between these microphones since it is made up of a large number of uncorrelated-distributed sources. Also, through model-scale test this was shown to be a valid assumption (for example, see Fig. 4). From the examination of model-scale jet noise results, and previous experience with engine noise data, the broadband noise from the engine in the far field at higher frequencies, such as in the vicinity of the fan BPF tone, is expected to be what is known as "fan broadband noise" and not jet noise. Since no coherence is obtained for the broadband noise in the region where fan broadband noise is expected, it appears that fan broadband noise also has a distributed-uncorrelated source region.

The fan broadband noise is radiated out of the fan ducts. Therefore it is distributed over a region that is comparable to the dimensions of the fan duct. For the present engine the fan-duct exit diameter was of the order of from 7 to 8 ft. This is large in comparison to wavelength at frequencies greater than about 500 Hz. For example, the wavelength of sound at 500 Hz is 2 ft, so that the fan exit diameter is about four times the wavelength. This itself is not sufficient to cause the signals between two widely separated far-field microphones to be uncorrelated. What is needed is that the sources themselves also be uncorrelated. Thus lack of broadband coherence between far-field microphones at frequencies where fan broadband noise is expected indicates that it is uncorrelated and distributed. This result is in reasonable agreement with the mechanisms of fan-noise generation.

Concluding Remarks

This paper has shown how a coherence function technique,[5] that uses simultaneous signals from three microphones, can be used to separate the engine components such as fan, core, and jet noise. The validity of the technique was demonstrated by a model-scale proof-of-concept experiment. Following that, the technique was applied to the data from a large high bypass ratio engine (JT9D). Core noise was derived by using two core nozzle microphone signals and a far-field microphone signal. The fan-noise component was derived using fan-duct and far-field microphone signals. Jet noise could be separated by subtracting fan and core components from the total noise. The advantage of the method is that individual components can be separated (without the influence of extraneous noise contamination) directly. Most other methods need prior knowledge of other noise components, spectral shapes, directivities, and so on.

The technique was also used with signals from three microphones external to the engine. With these signals, it was possible to separate the sum of core and fan noise from jet noise using the assumptions of Parthasarathy et al.[7] This capability to apply the technique to far-field microphone signals alone is very significant since, in many instances, it is impossible to install internal microphones without engine hardware modifications. Also, since most noise tests include far-field microphones anyway, it becomes possible to use the coherence technique without additional instrumentation. Only requirements will be to record the signals of interest simultaneously. The coherence analysis also usually requires somewhat longer tape recordings than usually used in engine noise tests. For the present work, 3 min of data were found satisfactory.

The engine broadband noise, at higher frequencies, did not satisfy the assumption required for the signal enhancement technique that the signal due to the component of interest be well correlated between the chosen microphones. This was believed to be because of the higher frequency broadband noise sources being uncorrelated and distributed over a region of size comparable to the diameter of the engine which in turn was large compared to the wavelength at frequencies greater than 500 Hz.

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