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Conditioned Pressure Spectra and Coherence Measurements in the Core of a Turbofan Engine

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CONDITIONED PRESSURE SPECTRA AND COHERENCE MEASUREMENTS IN THE CORE OF A TURBOFAN ENGINE*

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Abstract

Multiple and partial coherence functions and the corresponding conditioned coherent output spectra are computed between fluctuating pressures measured at two locations within the tailpipe of a turbofan engine and far-field acoustic pressure. The results are compared with the ordinary coherent output spectrum as obtained between a single tailpipe pressure measurement and the far-field acoustic pressure. The comparison indicates apparent additional "coherent output" (i.e., core-noise) beyond that detectable with an ordinary coherence measurement, thus suggesting the tailpipe as a core-noise source region. Further evidence suggests, however, that these differences may be attributed to the presence of transverse acoustic modes in the tailpipe and that the tailpipe is not, in fact, a significant source region.

Introduction

As part of a program to investigate the nature and significance of turbofan core-noise sources, pressure measurements were made at various locations in the core of a YF-102 turbofan engine, simultaneously with far-field acoustic measurements. Earlier analyses of the data using ordinary coherence and correlation techniques[1,2] have demonstrated that at frequencies below about 200 Hz, the combustor could be identified unambiguously as the major source of core-noise and as a significant contributor to the overall far-field noise at operating conditions up to about 60 percent of maximum fan speed. These same techniques are able to account for additional core-noise (not necessarily traceable to the combustor) at frequencies well above 200 Hz. However, this additional directly measureable core-noise is not sufficient to account for the differences between measured total noise and predicted fan plus jet noise. Furthermore, the source of this additional core-noise detectable beyond 200 Hz has not been specifically identified. A possible source of this additional noise is the tailpipe, where incident turbulence on, or flow separation from a centerbody and its support struts may produce some turbulent mixing.

In reference 3, using a novel two-probe coherence technique, Krejsa has shown that a very accurate accounting of the core-noise can be made to frequencies at least up to 1 kHz, and at operating conditions as high as 95 percent of maximum fan speed. The technique, however, does not address the issue of the origin of the core-noise. If such information is desired, then the relationship between the fluctuating pressures at various locations within the core as well as between the core pressures and the external acoustic field must be examined in somewhat more detail.

The purpose of this paper is to present the results of a preliminary examination of pressure measurements in the YF-102 core using conditioned spectral analysis. The intent is to use conditioned spectral analysis as a diagnostic device to determine whether or not the tailpipe is a significant source region for core-noise.

Engine, Instrumentation, Data Processing

Engine and Test Site

The test program was conducted on an AVCO-Lycoming YF-102 turbofan engine which has a bypass ratio of 6 and a rated thrust of 33 kN. This engine has a 1-m diameter fan and a core consisting of seven axial compressor stages, one centrifugal compressor stage, a reverse-flow annular combustor, and a four-stage turbine. The exit diameter of the core nozzle was 42 cm and the engine was operated with a bellmouth inlet. A cutaway illustration of the engine is shown in figure 1.

All tests were conducted at an outdoor acoustic test site with a hard surface ground plane. The engine was suspended from the test stand with its centerline 2.9 m above the ground plane (fig. 2). The far-field microphone array consisted of sixteen 1.27-cm diameter condenser microphones placed on a 30.5-m radius arc centered approximately 1.2 m upstream of the primary nozzle exit plane. The microphones were spaced 10° apart from 10° to 160°, measured from engine inlet axis. All microphones were mounted at ground level to minimize problems associated with ground reflections, and were fitted with windscreens. To obtain the phase information shown later, a single near-field microphone was used, located at an angle of 120°, 2 m from the nozzle exit plane.

Test Conditions

Simultaneous internal (i.e., core) fluctuating pressure and far-field acoustic measurements were made at eight different fan speeds at approximately equal intervals between 30 and 95 percent of maximum speed (7600 rpm). The corresponding range of combustor temperatures and core jet exhaust velocities were from 810 K, 98 m/sec to 1375 K, 314 m/sec.

Internal Probes

The dynamic pressure measurements within the engine core were made simultaneously with the far-field acoustic pressure measurements. Their number and locations were: two just downstream of the compressor exit and 2 cm apart; one at the combustor inlet; two within the annular combustor itself, both at the same axial location but separated 90° circumferentially; and two within the core nozzle, one just downstream of the turbine at the nozzle entrance and one close to the nozzle exit plane. This paper, however, is concerned only with the results

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obtained from the pressure measurements at the two nozzle locations (see fig. 3), and a single far-field microphone (120°), as well as the single near-field microphone mentioned earlier. Spectral data from the other internal probes, as well as additional far-field data, may be found in reference 4. The pressure probes used for the internal measurements were of the "semi-infinite" waveguide variety and a detailed description of their design and response characteristics may be found in references 1 and 2.

Data Acquisition and Processing

The signals from the internal probes and far-field microphones were FM-recorded on magnetic tape in 2-minute record lengths for later processing. The internal probes and far-field microphones were calibrated with a pistonphone before and after each day's running. The auto- and cross-spectra used to compute the conditioned spectral density matrices were obtained by off-line processing of the taped data on a two-channel fast Fourier transform digital signal processor with built-in a-d converters and 120 dB/octave anti-aliasing filters. The processor was capable of direct computation of up to a 4096 member ensemble average of a 1024 point forward or inverse Fourier transform to yield either time domain (correlation) or frequency domain (amplitude and phase spectra, transfer function, and coherence) information. The digital spectra produced by the processor were then transmitted to a central computer with which it was interfaced to perform the final computations necessary to obtain the conditioned spectra and associated multiple coherence functions.

Data Analysis

The essential notion utilized in this paper is as follows. It is presumed that all core-noise sources, whatever their origin, supply linear contributions to the fluctuating pressure at the tailpipe inlet, T_1, or at the nozzle exit, T_2, or both (see fig. 3). Hence, conditioning out, or removing, the independent linear contributions of the pressure at T_1 and T_2 from the total measured far-field spectrum leaves only non-core-noise contributions (such as fan and jet noise). The difference between the measured far-field spectrum and this conditioned far-field spectrum should, therefore, be a measure of the core-noise. This difference is formally called the multiple coherent output spectrum. A comparison of the multiple coherent output spectrum with the ordinary coherent output spectrum computed between, say, T_1 and the far-field, may then shed some valuable insight into the nature of the pressure field in the tailpipe and a possible origin of non-combustor core-noise.

The conditioning out, or removal, of the independent pressure contributions from the two tailpipe locations to the far-field pressure is not a simple subtractive process: the pressures measured at each of the two locations are not completely independent.

This, in a simplified form, is schematically illustrated in figure 4. Consider the two shaded areas together to represent the linear contributions of the two fluctuating tailpipe measurements to the far-field pressure measurement. The portion of the two measurements which correlate (i.e., are redundant) is represented by the overlapping region. In order to determine the sum of the independent contributions, the overlapping region must be assigned to just one of the two circular areas and the remaining "crescent" shaped area added back in.

The circular area on the right-hand side of figure 4 represents the ordinary coherent output spectrum between one of the tailpipe pressures and the far-field pressure, the crescent-shaped area represents the partial coherent output spectrum between the other tailpipe pressure and the far-field pressure, and the total area represents the multiple coherent output spectrum between the tailpipe pressures and the far-field pressure. The technique whereby the common, or correlating, information is appropriately accounted for is known as conditioned spectral analysis and is described in reference 5. In order to implement the computations for the present problem, the following procedure is used, following the notation suggested in reference 5.

The two tailpipe measuring stations are denoted as 1 and 2, referring to the upstream and downstream locations, respectively. The pressures measured at these locations are considered as "inputs" to a system in which a single far-field measurement is considered as the "output," and is denoted as measurement 3. With this notation a 3x3 matrix of complex auto- and cross-spectral densities, each element of which is a function of frequency, between the pressures can be formed:

$$G_{ij} = \left\{ \begin{matrix} \underline{G_{11}} & \underline{G_{12}} & \underline{G_{13}} \\ G_{21} & \underline{G_{22}} & \underline{G_{23}} \\ G_{31} & G_{32} & \underline{G_{33}} \end{matrix} \right\} \text{A (measured)}$$

The underlined elements are computed directly from the measured pressures by the FFT analyzer, and the remaining elements are obtained by the relation:

$$G_{ji} = G^*_{ij}$$

where the * denotes complex conjugate. The matrix G_{ij}, then, is obtained entirely from measured data. The diagonal elements are the auto-spectra, and the off-diagonal elements are the cross-spectra.

The ordinary coherence function at any frequency f between, say, input 1 and the output is obtained from[5]:

$$\gamma^2_{13}(f) = \frac{|G_{13}(f)|^2}{|G_{11}(f)|\,|G_{33}(f)|} \tag{1}$$

The product of γ^2_{13} and the measured output spectrum is called the ordinary coherent output spectrum. In the absence of input measurement contamination, this ordinary coherent output spectrum would represent the linear contribution of the pressure at T_1 to the far-field acoustic pressure (i.e., the "output") at station 3.

The linear contribution of the pressure at input 1 to the pressure at the other input, T_2, and to the pressure at the output can be removed, or conditioned out, through the following relations[5]:

$$G_{ij.1} = G_{ij} - L_{1j}G_{i1} \qquad (i,j = 1,2,3) \tag{2}$$

where L_{ij} is a complex frequency response function given by:

$$L_{ij} = \frac{G_{ij}}{G_{ii}} \qquad (3)$$

That is, a new spectral density matrix is formed by application of equations (2) and (3) to the elements of the measured spectral density matrix, A, which is reduced to:

$$G_{ij.1} = \left\{\begin{matrix} 0 & 0 & 0 \\ 0 & G_{22.1} & G_{23.1} \\ 0 & G_{32.1} & G_{33.1} \end{matrix}\right\} B$$

with $G_{32.1} = G^{*}_{23.1}$.

The elements in the conditioned spectral density matrix above may be interpreted as the spectra which would be measured if input 1 were "turned off." That is, $G_{22.1}$ is the auto-spectrum of input 2 with the linear effects of input 1 removed; $G_{23.1}$ is the cross-spectrum between 2 and 3 with the effects of input 1 removed, and so forth.

The conditioned spectral density matrix B can be reduced to a single element by removing the linear effects of input 2, through the following equations:

$$G_{ij.1,2} = \left\{\begin{matrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & G_{33.1,2} \end{matrix}\right\} C \qquad (4)$$

where

$$G_{33.1,2} = G_{33.1} - L_{23}\, G_{32.1}$$

and

$$L_{23} = G_{23.1}/G_{22.1}$$

The single element $G_{33.1,2}$, given by equation (4), may be interpreted as the auto-spectrum of the far-field acoustic pressure (i.e., the output) with the linear effects of both input 2 and input 1 removed. With the assumption that all core-noise sources manifest themselves as fluctuating pressure at T_1 or T_2 or both, then $G_{33.1,2}$ represents the spectrum which would be measured if the core-noise were removed. That is, it represents all the other turbofan noise sources.

The difference between the measured far-field pressure spectrum, G_{33}, and the part of the far-field spectrum with the core-noise removed must be the core-noise itself. Schematically we can write:

$$G_{\text{core-noise}} = G_{\text{total}} - G_{\text{non-core-noise}}$$

or

$$G_{3:1,2} = G_{33} - G_{33.1,2} \qquad (5)$$

where the term on the left-hand side is that part of the auto-spectrum in the far-field due to the linear contributions of the pressure at 1 and 2, and is called the multiple coherent output spectrum.

Recalling that it was presumed that all core-noise sources, regardless of their origin, are manifested as fluctuating pressure at T_1 or T_2 or both, then, subject to appropriate assumptions and restrictions, this multiple coherent output spectrum may be interpreted as the core contribution to the far-field noise when any independent source information at T_1 and T_2 is appropriately accounted for. Hence, the following possibilities exist: (1) if there is no independent source information between T_1 and T_2 (i.e., core-noise source information at T_1 and T_2 is redundant), then the multiple coherent output spectrum will not differ from the ordinary coherent spectrum as measured between, say, T_1 and the far-field. Referring back to figure 4, this is equivalent to the overlapping region being large and the "crescent" shaped region being very small; that is, the two circular regions would be nearly congruent; (2) if there is independent source information between T_1 and T_2, there will be differences between the ordinary and multiple coherent output spectra at those frequencies associated with the sources. Note, however, that the existence of such differences between the multiple and ordinary coherent output spectra does not prove the presence of new source information, it only admits the possibility.

Coherence Results

The results of the computations outlined in the previous section are shown in figures 5(a) to (f), which represent engine operating conditions between 30 and 75 percent of maximum fan speed. The dashed curve in each of the figures is the ordinary coherent output spectrum between the measured pressure at the tailpipe inlet (T_1) and the far-field acoustic pressure measured at 120° relative to the inlet axis. The solid curve in each of the figures is the corresponding multiple coherent output spectrum, as computed from equation (5). Finally, for reference purposes only, the total measured acoustic pressure spectra at the far-field are shown with the broken lines.

The most obvious feature of these results is the difference between the ordinary coherent output spectra and the corresponding multiple coherent output spectra over a broad range of frequencies from about 400 to 700 Hz. Under the assumption that the input measurements (i.e., the pressures at T_1 and T_2) are contaminant or "noise" free, then these differences would be interpreted as indicating the presence of additional "coherent output" not otherwise detectable with a single pressure measurement in the tailpipe. That is, in the frequency range between about 400 to 700 Hz, the tailpipe contains apparent distributed or multiple independent core-noise sources.

In arriving at this conclusion, even in just a qualitative sense, the assumption that the input pressure measurements are contaminant-free is crucial. In the present context, input measurement contamination, or "noise", is defined as that portion of the input signal which would not be coherent with the output if the output were contaminant-free. Input contamination may be due to non-linearities, local or convecting hydrodynamic pressure disturbances at the measuring points (i.e., pseudosound) which are not acoustic in character and hence do not radiate to the far-field, multiple independent or distributed source characteristics, or the presence of higher-order acoustic modes which do not propagate or propagate greatly attenuated. Additionally, the actual output as represented by the total measured acoustic pressure in the far-field is certainly not contaminant-free. It contains contributions from the jet and fan which do not correlate with the core-noise. These latter sources, of course, are precisely the quantities from which we are trying to distinguish the core-noise.

For actual engine data, then, there is no a priori way of quantifying the effects of input measurement contamination on the coherence measurement. Qualitatively, however, input measurement contamination always serves to reduce the value of the coherence function. The resulting coherent output spectra can, therefore, at least be interpreted as the minimum contribution of the measured inputs to the output if other appropriate causal relations are satisfied.[1]

The reduction in the computed ordinary coherent output due to contamination resulting from multiple or distributed source characteristics can be overcome by computing the multiple coherent output spectrum. However, if the single measured input used for computing the ordinary coherent output spectrum has proportinately more contamination associated with non-linearities or non-propagating signal (at a given frequency or frequency range) than the second of the two inputs used when computing the multiple coherent output spectrum, then the effect of contamination cannot be distinguished from the effects of multiple or distributed source characteristics.

The observed differences, therefore, between the ordinary coherent output spectra and the multiple coherent output spectra seen in figure 4 may be due to contamination at the upstream pressure measurement as well as multiple or distributed source characteristics within the tailpipe. Thus, the qualitative conclusion that the tailpipe is a source region for core-noise is premature. In fact, as will be discussed below, the evidence seems to suggest that the apparent additional coherence output shown in figures 5(a) to (f) is due to high levels of contamination at the probes, and that the tailpipe is not a significant source region for core-noise, at least for the present engine.

Phase Measurements

In figure 6(a) is shown, for the 43-percent operating conditions, the phase difference between the fluctuating pressures at T_1 and T_2. The solid line is the phase as obtained directly from the cross-spectrum between T_1 and T_2. The dashed line is the phase obtained by using the pressure measured at an external near-field microphone as a reference: that is, the difference in the cross-spectral phases between the pressure at T_1 and the near-field microphone and the pressure at T_2 and the near-field microphone. In figure 6(b) is shown the same information for the 75-percent operating condition.

(The near-field microphone described earlier was used as a reference instead of the far-field microphone to minimize the time delay between the internal and external signals. This reduced time delay eliminated the need for introducing a large precomputation delay in computing the cross-spectrum and hence permitted a significantly larger number of data samples to be averaged by the FFT processor. This reduced the statistical variance in the computed cross-spectrum.)

The figures clearly show the two phase measurements in close agreement except in the range of frequencies between about 400 and 700 Hz, the same range over which there are significant differences between the ordinary and multiple coherent output spectra in figure 5. Within this frequency range, therefore, the fluctuating pressure which contributes to the cross-spectral phase within the tailpipe, does not contribute to the phase outside the tailpipe. That is, at these freqencies, the coherent pressure disturbances within the tailpipe are dominated by information which do not radiate outside the tailpipe, and hence may be classified as measurement contamination. There is, of course, no way with the present data to demonstrate that only part of the difference between the ordinary and multiple coherent output spectra seen in figure 5 is measurement contamination and the balance is independent source information in the tailpipe. However, it seems unlikely that the new source information and measurement contamination would bracket precisely the same frequency range.

On this basis, then, it is concluded that the differences between the ordinary and multiple coherent output spectra seen in figure 5 may be reconciled on the basis of input measurement contamination rather than distributed or multiple source characteristics. This conclusion may be reinforced if we can identify a specific contaminant consistent with the frequency range seen above.

Identification of Contamination

Hydrodynamic pressure disturbances due to turbulence (i.e., pseudosound) are often advanced as the primary sources of input measurement noise, or contamination, when conducting a coherence analysis of the types of measurements described in this investigation. One would expect, however, that the spectrum of such turbulence contamination would Strouhal scale, and for fixed geometry would have its frequency range linearly shift with the flow velocity within the tailpipe. For the set of engine operating conditions presented, the velocity within the tailpipe ranges from about 90 m/sec at the 30-percent condition to about 210 m/sec at the 75-percent condition: more than a factor of two. Such a shift in the frequency range associated with the contamination obtained from figures 5 and 6 is not observed. What has been identified as a contaminant remains relatively fixed in its frequency range of 400 to 700 Hz, throughout the set of operating conditions.

Furthermore, in reference 1, the cross-correlation between the two tailpipe pressure signals (low pass filtered at 1600 Hz) was shown to have a single positive peak at a delay time consistent with the speed of sound in the tailpipe. No time delay associated with a turbulence convection velocity was found within the tailpipe. Hydrodynamic pressure fluctuations may, therefore, be ruled out as the source of the contaminant identified in figures 5 and 6.

(This conclusion only applies to the contamination identified by virtue of the observed differences between the ordinary and multiple coherent output spectra shown in figure 5, and the phase information shown in figure 6. It is not meant to imply that there is no turbulence contamination of the pressure measurements in the tailpipe. Turbulence contamination which is not coherent between the tailpipe probes would not contribute to the corresponding cross-spectral phases. Hence, purely local turbulent pressure fluctuations, or convecting turbulence which decays before reaching the downstream pressure probe, may contaminate the coherence measurements. Such contamination, in fact, is likely responsible for much of the differences between the multiple coherent output spectra and the total measured far-field spectra. This type of contamination, or measurement "noise," however, may be removed by the two-probe coherence technique described by Krejsa in ref. 3 and applied to this engine.)

As indicated earlier, the presence of any transverse acoutic modes which may propagate within the tailpipe but not radiate outside the tailpipe, or radiate very inefficiently, serves to act as a contaminant. Straightforward calculations indicate that the lowest order transverse mode which begins to propagate in the tailpipe is the first circumferential mode (i.e., the 1,0 mode). At the lowest operating condition being considered (30 percent of maximum fan speed), the (1,0) mode begins to propagate at the upstream tailpipe position at frequencies above about 460 Hz. At the tailpipe exit this mode cuts off at frequencies below about 710 Hz. These cutoff frequencies, which represent the range in which measurement contamination has been identified, change by only about 1 to 2 percent through the entire set of operating conditions because of the offsetting effects of simultaneously increasing temperature and Mach number within the tailpipe as engine speed increases.

This is highly consistent with the data of figures 5 and 6. Combined with the cross-correlation data of reference 1, which indicates a single acoustic delay time in the tailpipe at frequencies up to 1600 Hz, it is concluded that the observed differences between the ordinary and multiple coherent output spectra result from measurement contamination due to transverse modes in the tailpipe and not from multiple or distributed source characteristics.

Now, any aeroacoustic sources within the tailpipe will be flow related by virtue of the turbine exhaust flowing over the internal nozzle surfaces, the nozzle plug, or support struts. Such sources, if present, are likely to be multiple, or at least distributed, in nature, and therefore unable to be characterized by a spacially isolated measurement. Consequently, since the effects of multiple or distributed source characteristics cannot be detected, it is concluded that the tailpipe is not a significant source region for core-noise.

Summary and Concluding Remarks

Conditioned pressure spectra were computed between two widely-spaced locations in the tailpipe of a YF-102 turbofan engine and a far-field microphone. A comparison of the associated multiple coherent output spectra with the corresponding ordinary coherent output spectra showed significant differences over a broad range of frequencies. The frequency range over which these differences were observed, however, remained essentially unchanged over the complete set of engine operating conditions examined.

Phase measurements obtained directly from the cross-spectrum between the two tailpipe probes and indirectly using an external near-field microphone as a reference were presented. These measurements, together with velocity scaling arguments, were used to conclude that the differences between the multiple and ordinary coherent output spectra could be reconciled on the basis of measurement contamination due to the presence of transverse modes in the tailpipe. The tailpipe, therefore, was found not to be a significant source region for core-noise.

In reference 1 it was demonstrated that the combustor could be unambiguously identified as the source of core-noise at frequencies below about 200 Hz. The correlation delay times across the turbine for the source information, however, corresponded to convection rather than acoustic speeds. In reference 3 it was shown that significant levels of core-noise can be detected to frequencies up to about 1 kHz. Hence, if the tailpipe can be excluded as the origin of this additional core-noise, then combustor-turbine coupling must be considered as a candidate mechanism.

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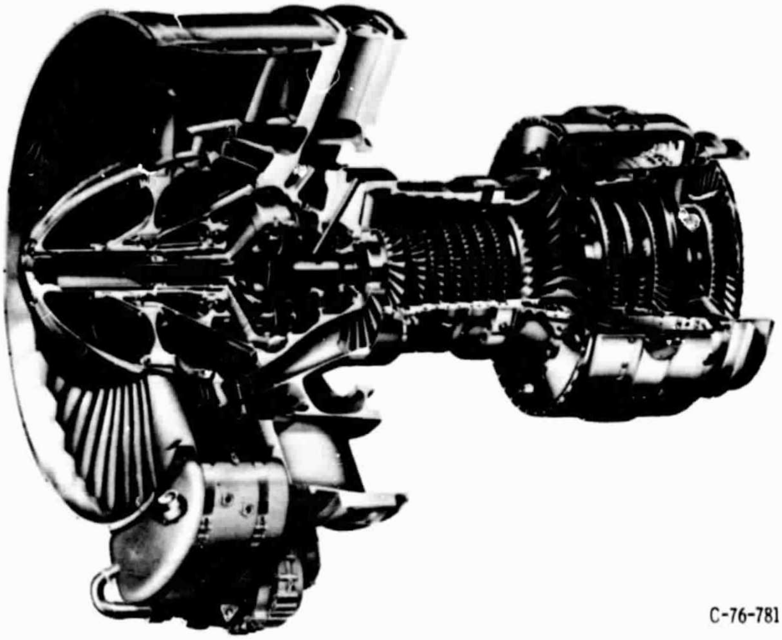
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Figure 1. - Cutaway illustration of YF-102 turbofan engine.

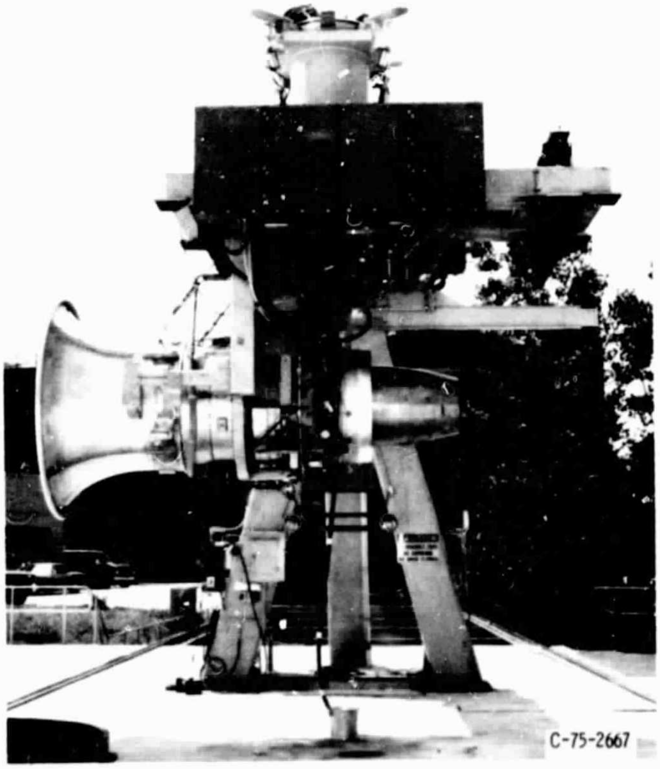


Figure 2. - YF-102 engine on test stand.

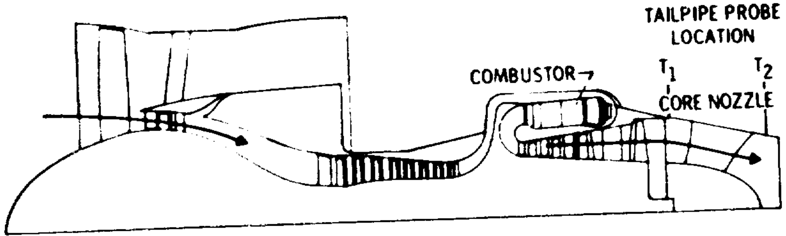


Figure 3. - Cross-section of YF-102 showing location of tailpipe probes.

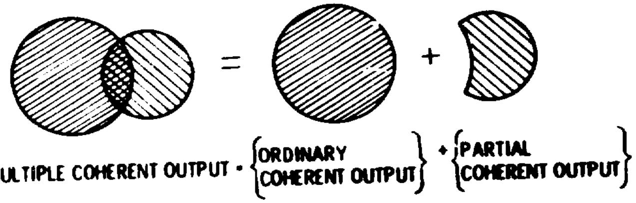
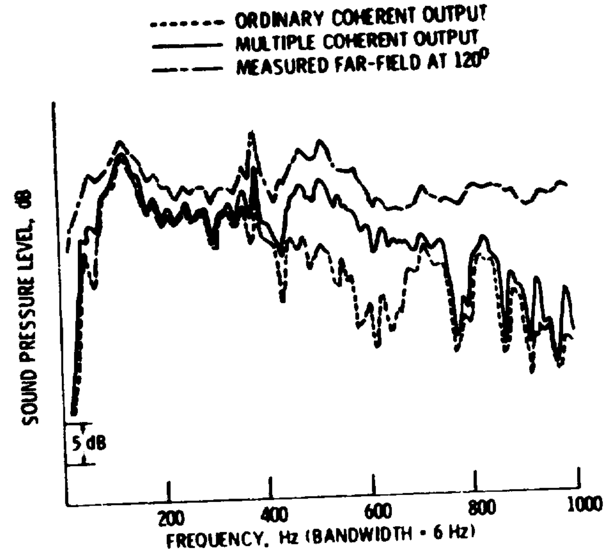
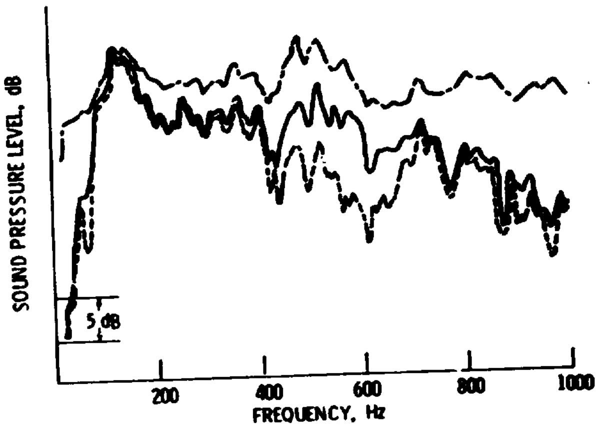


Figure 4. - Composition of coherent outputs.



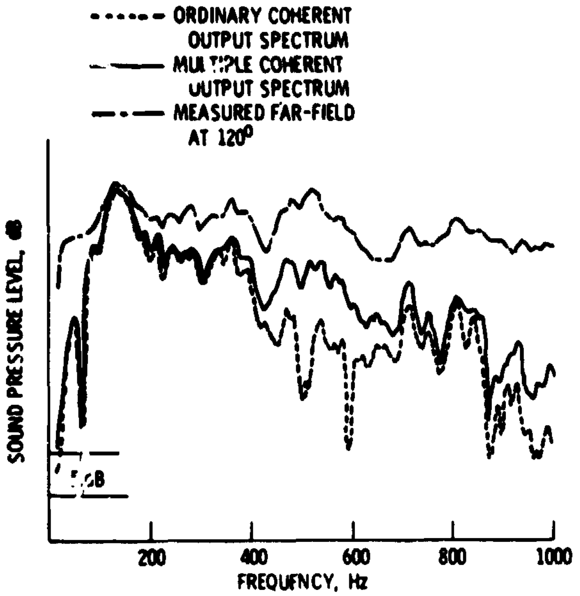
(a) 30% OF MAXIMUM FAN SPEED.

Figure 5. - Comparison of ordinary and multiple coherent output spectra.



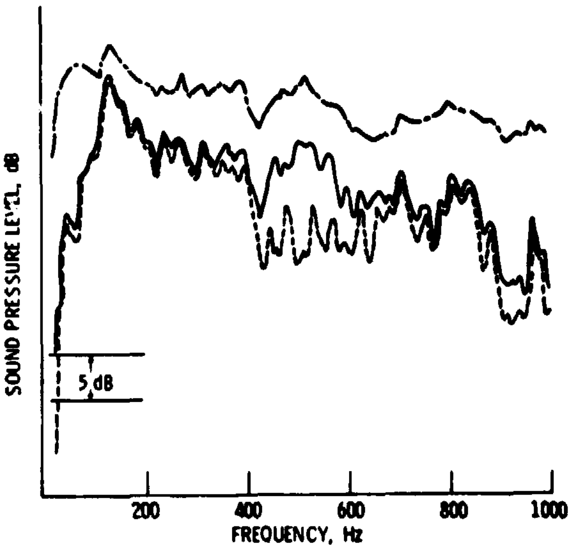
(b) 37% MAXIMUM FAN SPEED.

Figure 5. - Continued.



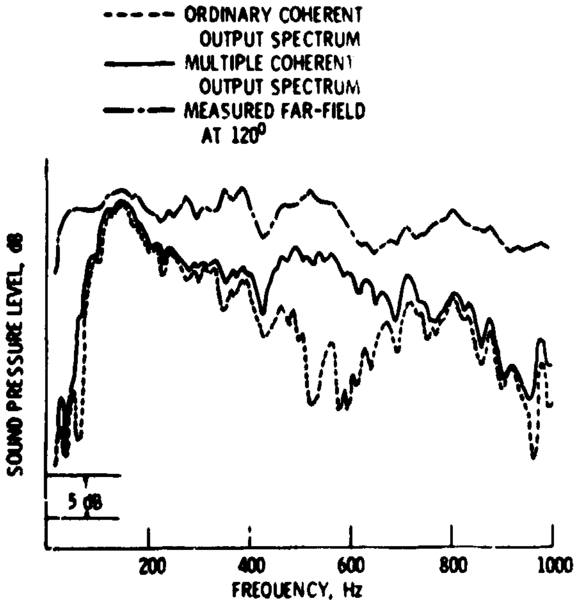
(c) 43% OF MAXIMUM FAN SPEED.

Figure 5. - Continued.



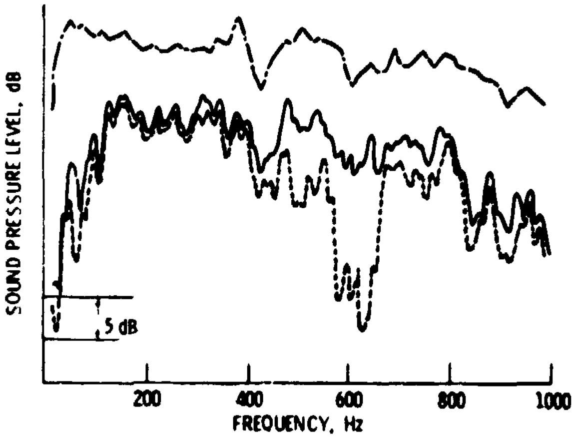
(d) 50% MAXIMUM FAN SPEED.

Figure 5. - Continued.



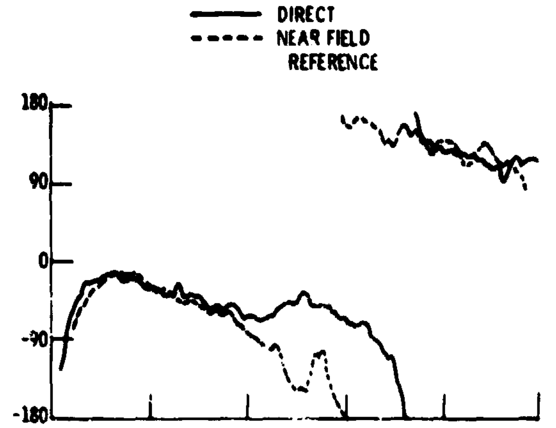
(e) 60% MAXIMUM FAN SPEED.

Figure 5. - Continued.

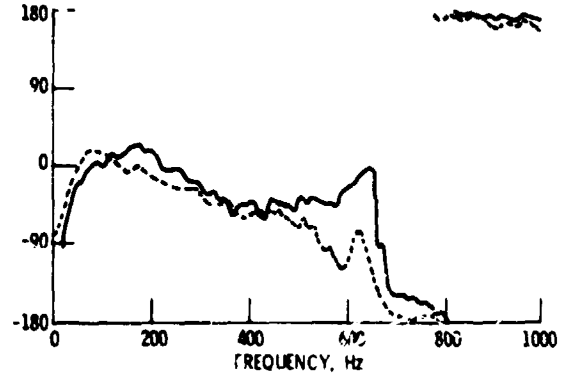


(f) 75% MAXIMUM FAN SPEED.

Figure 5. - Concluded.



(a) 43% MAXIMUM FAN SPEED.



(b) 75% MAXIMUM FAN SPEED.

Figure 6. - Phase difference between tailpipe pressures.