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NASA TM X-73587

(NASA-TM-X-73587) CORE NOISE MEASUREMENTS
ON A YF-102 TURBOFAN ENGINE (NASA) 27 p HC
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CORE NOISE MEASUREMENTS ON A YF-102 TURBOFAN ENGINE

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ABSTRACT

Core noise from a YF-102 high bypass ratio turbofan engine was investigated through the use of simultaneous measurements of internal fluctuating pressures and far field noise. Acoustic waveguide probes, located in the engine at the compressor exit, in the combustor, at the turbine exit, and in the core nozzle, were employed to measure internal fluctuating pressures. Spectra showed that the internal signals were free of tones, except at high frequency where machinery noise was present. Data obtained over a wide range of engine conditions suggest that below 60% of maximum fan speed the low frequency core noise contributes significantly to the far field noise.

INTRODUCTION

In the past several years considerable progress has been made in reducing the noise generated by jet-aircraft engines. The two largest sources of engine noise, the fan and the jet exhaust, have been significantly reduced. Further treatment of these sources may not reduce the overall engine noise because an acoustic threshold may have been reached. This threshold consists of noise generated by heretofore poorly understood sources within the engine core. One of the more likely sources of far field noise originating from the engine core is the combustion process where large amounts of chemical energy are released.

Recently, many theoretical and small scale experimental studies concerned with aircraft engine core noise have been conducted with particular emphasis on the low frequency noise caused by combustion. However, because of the effort and expense involved, only a few experiments have been made with aircraft engines and reported in the literature. Two such experiments aimed at studying low frequency core noise were performed with microphones placed outside the engine only (refs. 1 and 2). In both cases the exhaust nozzles were oversize to reduce the primary jet velocity and the associated jet exhaust noise, thus allowing the core

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noise to be detected in the far field. Two other investigations combined both internal and external measurements for the determination of core engine noise (refs. 3 and 4). However, their results were limited because only two probes were placed in the engine core.

At the NASA Lewis Research Center, tests have been conducted to determine the characteristics of combustion and other core noises and their propagation through the engine core to the far field using an AVCO-Lycoming YF-102 high bypass ratio turbofan engine. The overall objective of the program was to measure the noise in the combustor at various engine operating speeds and to determine its propagation (1) upstream to the compressor exit, (2) downstream through the turbine and core nozzle, (3) to the near field, and (4) to the far field. The results indicate the range of engine operating conditions where the combustor or other core engine noises influence or dominate the far field acoustic signal.

It is the purpose of this paper to describe the engine test program and to present some of the results obtained. A separate paper (ref. 5), reports the use of cross-correlation and coherence techniques on the present data in order to determine acoustic source propagation through the engine core to the far field.

ENGINE, INSTRUMENTATION, AND DATA PROCESSING

Engine

The AVCO-Lycoming YF-102 engine is a bypass ratio 6, two spool, turbofan engine with a rated thrust of 33 kN. The engine core consists of an eight stage compressor, a reverse flow annular combustor and a four stage turbine. The compressor, consisting of seven axial and one centrifugal stage, is driven by the first two (high pressure) stages of the turbine. The fan and supercharger are driven through a 2.3 to 1 speed reduction gear by the last two (low pressure) turbine stages.

All tests were conducted at an outdoor engine test stand with the engine centerline 2.9 m above a hard surface ground plane. The engine was configured with a bellmouth inlet and separate core and fan exhaust nozzles. The core and fan nozzle areas were 0.136 and 0.361 square meters, respectively. A photograph of the engine mounted on the test stand and a cutaway of the engine are shown in figure 1.

Measurements were made at eight fan speeds between 30% and 95% of maximum speed (7600 rpm). A summary of the test conditions, including pressures and temperatures in the core engine, is presented in table I.

Internal Probes

Dynamic pressure probes were placed in the engine core at seven different locations (fig. 2) as follows: two just downstream of the compressor exit about 2 cm apart; one at the combustor entrance; two within the combustor at the same axial location but separated 90° circumferentially; and two within the core nozzle, one just downstream of the turbine at the turbine exit and one close to the nozzle exit plane.

The transducers used were conventional 0.635 cm diameter pressure response condenser microphones. To avoid direct exposure of the microphones to the severe environment within the core, they were mounted outside the engine and the fluctuating pressure in the engine core was communicated to the transducers by "semi-infinite" acoustic waveguides.

A drawing of a typical acoustic waveguide probe is shown in figure 3. The microphone was flush mounted in the acoustic waveguide through a support block and housed in a pressure chamber. Attached to the block was a 5/8 cm diameter sensing tube on one end and a coil of tubing of the same diameter, 30 m long, on the other. The sensing tube of each probe was flush mounted at each of the measuring locations within the engine core. A regulated nitrogen purge flow was maintained in the sensing line to protect the microphone from hot core gases. Static pressure was balanced across the microphone by means of a small vent hole connecting the pressure chamber and sensing line. A schematic diagram of a typical core probe installation is shown in figure 4.

The frequency response of the probes (phase and amplitude) were determined by comparison with a microphone identical to the one used in the probe using a symmetric placement with respect to the axis of a loudspeaker. The input to the loudspeaker was a signal from a white noise generator low pass filtered at 10 kHz.

The frequency response for a typical probe is shown in figure 5. The results indicated that the amplitude response of the probes was flat within ± 2 dB from 50 Hz to 1500 Hz. Similarly, the phase response of the probes was flat within about 5° up to 1500 Hz after accounting for the phase lag associated with the length of the sensing tube of each particular probe. Between 1500 Hz and about 3500 Hz the response was generally flat within ± 4 dB and $\pm 10^\circ$. Limitations of the calibration facility prevented accurate determination of response characteristics beyond 3500 Hz. With the exception of high frequency tones generated by the compressor and turbine, the core noise associated with this engine was confined to a frequency range well within the acceptable response region of the probes.

The effect of the nitrogen purge flow on probe response was also determined. The pseudosound generated by the nitrogen purge

flow through the probe was found to be a minimum of 20 dB below the core fluctuating pressure at the highest purge flow rate required in the engine tests.

The probe sensing tubes were required to cross the fan flow stream. In order to minimize flow-induced noise in the probe sensing tubes from the impinging fan stream flow, airfoil shaped struts attached to the core engine cowl and surrounding the tubes were used. A photograph of the engine with the probes and struts in place is shown in figure 6.

External Microphones

The far field microphones consisted of an array of sixteen 1.27 cm diameter condenser microphones on a 30.5 m radius circle centered on the exhaust plane of the core nozzle. The microphones were spaced 10° apart from 10° to 160° from the engine inlet axis, and were mounted at ground level to minimize the problems associated with ground reflections.

A near field microphone was placed on a stand at the engine centerline height (2.9 m), 1.65 m downstream of the nozzle exit plane and offset 0.95 m from the engine centerline.

Data Acquisition and Processing

The signals from the internal probes and far field microphones were FM-recorded on magnetic tape in two-minute record lengths for later processing. The internal probes and far field microphones were calibrated with a pistonphone prior to and at the end of each day's running. The data were analyzed on narrow band and one-third octave band spectrum analyzers which determined pressure level spectra referenced to 2×10^{-5} Pa.

The present one-third octave band spectra represent an arithmetic average of three independent samples taken within the two minute record length with corrections applied after averaging. The spectra measured by the internal probes were corrected for frequency response of the probes and ambient pressure. The error due to frequency response was described in the section Internal Probes. The level of the static ambient pressure within the test duct affects the sensitivity of the microphone cartridge. Corrections to the measured spectra of between +1 dB at the lowest engine speed and +4 dB at the highest were necessary to compensate for this effect. The sound pressure level spectra obtained from the external microphones were corrected for atmospheric absorption and the far field data were corrected to free field. The narrow band data reported herein are given as measured without any correction.

RESULTS AND DISCUSSION

Narrow band, one-third octave band, and cross correlation data were obtained by simultaneous measurements from probes located inside the engine core and microphones placed in the near and far field. The results are separated into two main categories: the first consists of internal measurements where the data from each engine component are presented separately, and the second consists of the relationships between internal measurements and the near and far field acoustic signals. Although the engine was tested at eight rotational speeds, for simplicity, data are presented for only four speeds: 30, 43, 60, and 85% of maximum. These data are considered representative of various conditions in the engine operating cycle.

Internal Measurements

As previously stated, internal dynamic pressure measurements were made in the compressor exit, combustor entrance, combustor, turbine exit, and core nozzle exit. Typical one-third octave band dynamic pressure level spectra at these locations for an engine fan speed of 43% are presented in figure 7. The spectra exhibit the broadband nature of the signal below 5000 Hz and the tonal content due to rotating machinery above 5000 Hz. However, these data by themselves do not indicate the origin or the propagation characteristics of the broadband signals and the tones, nor do they indicate whether the probes are measuring acoustic pressure, hydrostatic pressure fluctuations, or some combination of the two. To explore these points, the data for each component will be examined separately.

Compressor exit. - The pressure spectra presented in figure 8 were obtained by the downstream probe at the compressor exit (fig. 2). In figure 8(a), pressure level in the compressor exit is plotted as a function of one-third octave band center frequency for four engine speeds. The shapes of the spectra are similar for all speeds and as would be expected, the pressure level increases with increasing engine speed.

A narrow band spectrum with a range up to 20 000 Hz is shown in figure 8(b) for an engine speed of 43%. At frequencies below 6000 Hz, there are no dominant tones present. However, the spectrum displays an oscillatory nature over the entire frequency range. Above 8000 Hz there are strong tones in evidence which are the fundamental and harmonics of the blade passage frequencies of the various compressor stages. The last (centrifugal) stage of the compressor is closest to the probe and is responsible for the strongest tone (8235 Hz). The sixth and seventh compressor stages have the same number of blades and consequently generate a tone at a common frequency (11 438 Hz). The fourth and fifth stages also generate a tone at a common frequency (10 980 Hz). Tones corresponding to the respective blade passage frequencies of the first three compressor stages are not detected by the probe.

Although the high frequency tones thus have been accounted for, the low frequency pressure level oscillations have not. A normalized cross correlation of pressure fluctuation between the two probes placed 2.11 cm apart (fig. 2) near the compressor exit is shown in figure 9. The two signals, which are low pass filtered at 2000 Hz, correlate quite strongly at a positive time delay of 0.18 ms. The positive time delay means that the signal is traveling downstream, i.e. from the compressor to the combustor. Considering the distance between the probes, the time delay for an acoustic signal to travel between them is calculated to be 0.045 ms. The observed time delay is four times that. From this it is concluded that the low frequency signal is not the result of acoustic pressure fluctuation, but is caused by some convection phenomenon, possibly turbulence.

Combustor. - Two probes, 90° apart, were flush mounted in the combustor liner downstream of the igniter in the region where the combustion process comes to completion (fig. 2). The pressure spectra measured by one of these probes are shown in figure 10. In figure 10(a) one-third octave band combustor pressure spectra are presented for four engine speeds. At 30% speed there appears to be a tone near the 400 Hz center frequency which does not appear at any of the higher speeds.

Narrow band pressure spectra up to 2000 Hz are shown in figure 10(b). At the lowest engine speed, 30%, there is a sharp tone at 380 Hz which corresponds to the tone in the one-third octave band spectrum (fig. 10(a)). At all higher engine speeds the combustor spectra for this frequency range are free of well-defined tones. At the higher frequencies, 7000 to 16 000 Hz (not shown), compressor tones are noticeable but their levels are greatly attenuated. The tones which appear in all the spectra at 60 Hz are due to electrical noise.

Measurements at the combustor entrance, below 2000 Hz, show a spectrum similar in shape to that of the combustor but lower in level (fig. 7). Furthermore, a cross correlation between combustor and combustor entrance signals shows a positive time delay corresponding to the local speed of sound. Therefore, it can be assumed that the low frequency signal from the combustor is passing through the liner to the combustor entrance.

Core nozzle. - Two probes were placed in the core nozzle (fig. 2), one at the turbine exit and the other at the core nozzle exit. One third octave band pressure spectra obtained at these locations are presented in figure 11, again for four engine speeds. A strong tone in the turbine exit (fig. 11(a)) appears at 1000 Hz at the highest fan speed presented (85%). However, downstream at the core nozzle exit (fig. 11(b)) this tone is no longer evident.

Narrow band spectra to 2000 Hz from these probes at an engine speed of 43% are presented in figure 12(a). At the turbine exit,

excluding the 60 Hz electrical noise, there are spectrum peaks at approximately 125, 500, 870, and 1240 Hz which do not appear as pure tones but which are noticeable nevertheless. Downstream, at the core nozzle exit, these peaks are not apparent. At the present time it is not clear whether these peaks are caused by an acoustic or a flow convection phenomenon. A narrow band pressure spectrum to 2000 Hz measured at the turbine exit at an engine speed of 85% is presented in figure 12(b). At this high speed condition (excepting the 60 Hz electrical noise) a tone appears at 250 Hz and at every multiple thereof in the spectrum. Furthermore, at 125 Hz the tone level is a maximum. The dominant band that appears in the 1/3 octave band spectrum of figure 11(a) contains this tone. At this operating condition the turbine speed is 250 revolutions per second and is the most probable source of the 250 Hz tone and its harmonics. At the core nozzle exit, these tones are present but greatly attenuated.

Constant bandwidth spectra up to 10 000 Hz at the turbine exit and the core nozzle exit at 43% engine speed are presented in figure 12(c). The data measured at the turbine exit indicate sharp tones at the calculated blade passage frequencies of the last two turbine stages. Downstream, at the core nozzle exit, these same tones exist relatively unchanged except for a slight reduction in amplitude.

A normalized cross-correlation between the two probes in the core nozzle is shown in figure 13. The two signals correlate at a time delay of 0.55 msec. Considering the gas temperature (~ 640 K), flow velocity (~ 90 m/sec) and distance between probes (34 cm), the calculated time delay for an acoustic signal to travel between them would be .56 msec. This indicates that the signals being measured are predominantly acoustic.

Relationship of Internal to Far Field Measurements

Far field. - Directivity patterns taken from existing prediction techniques for low frequency core engine noise indicate a maximum at 120° from the engine inlet axis (ref. 6). Far field acoustic spectra at this angle are presented in figure 14. In figure 14(a), one-third octave band sound pressure level spectra are given for four engine speeds. A narrow band spectrum to 10 000 Hz at 43% speed as shown in figure 14(b) indicates the presence of many tones. These tones are the fundamentals and harmonics of the blade passage frequencies of the fan and the turbine. When measured in the core engine, the turbine tones appear sharp (fig. 12(c)); however, in the far field they appear "haystacked". This broadening of the tone is most probably due to propagation through the regions of high shear flow or turbulence associated with the fan and core jet mixing regions. At 85% speed, the far field sound pressure level spectrum shown in figure 14(c) contains four distinct tones. These tones correspond to the fan blade passage frequency and three harmonics. At this engine speed, the third

and fourth stages of the turbine generate tones at 15 950 and 14 590 Hz respectively. However, these turbine tones are not detected in the far field spectra at high engine speed.

Relationship of internal and external signals. - In order to relate the magnitude of each signal from location to location, one third octave band dynamic pressure level spectra for the in-duct (shown previously in fig. 7), near field, and far field measurements at an engine speed of 43% are shown in figure 15. There is an attenuation of about 15 dB between the combustor and the turbine exit in the region below 2000 Hz.

The near field levels are about 25 dB below those at the nozzle exit, and the far field levels are 50 dB below the nozzle exit, all at frequencies below 2000 Hz. Above 2000 Hz, the near and far field spectra are not broadband and indicate the effects of fundamentals and harmonics of tones emanating from the fan and turbine.

Cross-correlation techniques were used to determine the characteristics of the pressure signal propagation through the engine core to the far field. Cross-correlation functions between the fluctuating pressure at the core nozzle exit and the far field acoustic pressure at 120° from the engine inlet are shown in figure 16(a). Correlations between the fluctuating combustor pressure and far field acoustic pressure at the same angle are shown in figure 16(b). The time delay of the maximum or minimum correlation value, as appropriate, in each case corresponds to the acoustic propagation time between the engine probe and the far field microphone. The core nozzle exit to far field cross-correlation can be identified as one associated with pure propagation, but the combustor to far field cross-correlation cannot because of the negative value.

In reference 5, it was shown that for frequencies up to 250 Hz the phase and amplitude relationship between combustor pressure and far-field acoustic pressure involved a 180° phase shift (which accounts for the negative correlation) and an amplitude change proportional to frequency squared, indicating the combustor is in an acoustic source region. In contrast, a zero degree phase shift and an amplitude change independent of frequency were shown to prevail between the fluctuating pressure at the core nozzle exit and the far field acoustic pressure, indicating pure propagation.

Power. - The variation of low frequency acoustic power as a function of jet exhaust velocity is shown in figure 17. The acoustic power level was computed from signals between 50 and 2000 Hz only, the main region of interest for core engine noise. The far field acoustic power was computed in the usual manner from the microphone data. The acoustic power at the core nozzle exit was computed, on the assumption of an acoustic plane wave, as the product of the acoustic intensity and the area of the duct at the probe location. The intensity, I , for a moving stream is expressed in reference 7 as:

$$I = \frac{\bar{p}^2}{\rho c} (1 + M) \quad (1)$$

where

\bar{p}^2 local mean square pressure fluctuation
 ρ local density
 c local speed of sound
 M local Mach number

The core nozzle exit acoustic power level shown in figure 17 was computed from the following equation which is a product of a transformation of eq. (1), and the core nozzle exit area

$$FWL = SPL + 47.58 + 10 \log_{10} \frac{A \sqrt{T}}{p} (1 + M) \quad (2)$$

where

FWL sound power level, dB, ref. 10^{-15} watts
 SPL sound pressure level measured by probe, dB, ref. 2×10^{-5} Pa
 A area (square meters)
 T temperature (K)
 p pressure (pascals)

The effective jet exhaust velocity, V_E , given in figure 17 is arbitrarily defined for convenience as a simple measure of engine operating condition. It is a weighted velocity which accounts for the differences in mass flow and velocity of the fan and core at each engine condition, and is defined as:

$$V_E = \frac{BPR \cdot V_F + V_C}{BPR + 1}$$

where

V_F fan velocity
 V_C core velocity
 BPR engine by-pass ratio

It is seen in figure 17 that in the low velocity region (up to 150 m/sec) the power level calculated at the core engine exit is in close agreement with the power level calculated in the far field at 30.5 m. However, above 150 m/sec, the power level in the far field becomes considerably greater (10 dB at 250 m/sec) than the level in the nozzle exit region. Also, above a jet velocity of 150 m/sec, the far field acoustic power behaves as velocity to the eighth power which is indicative of jet mixing noise. This suggests strongly that below certain engine operating conditions (60% maximum speed in this case) where the jet noise is not significant, noise emanating from the engine core makes a significant contribution to the far field noise.

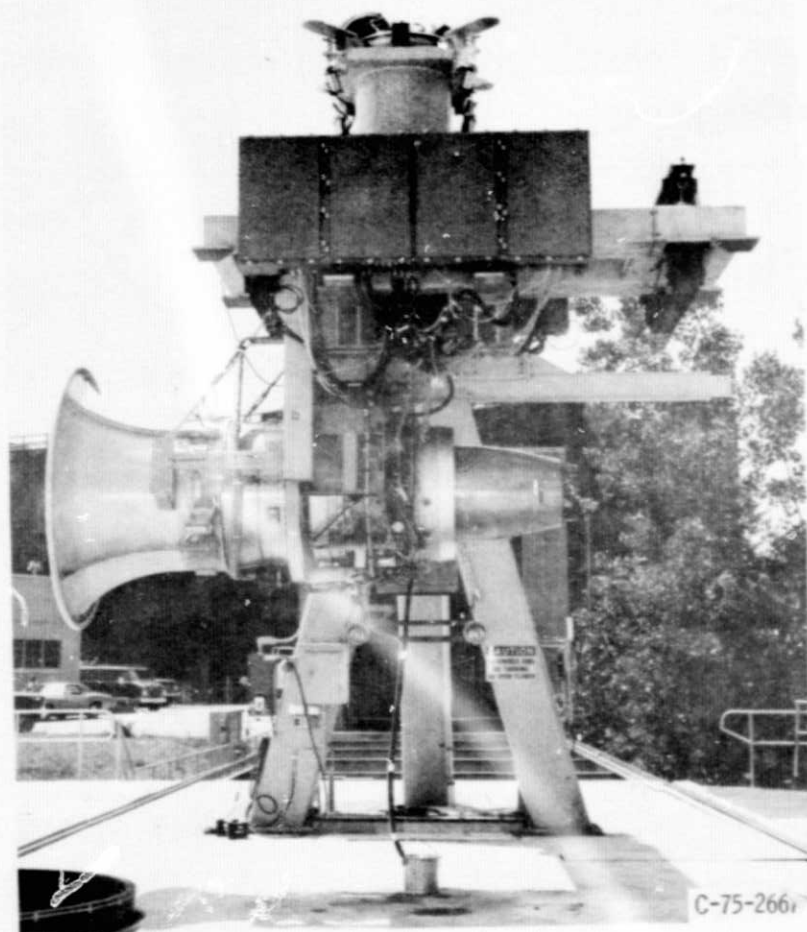
4. Burdsall, E. A., Brochu, F. P., and Scaramella, V. M., "Results of Acoustic Testing of the JT8D-109 Refan Engines," Pratt and Whitney Aircraft, East Hartford, Conn., PWA-5298, Nov. 1975; also NASA CR-134875.
5. Karchmer, A., and Reshotko, M., "Core Noise Source Diagnostics on a Turbofan Engine Using Correlation and Coherence Techniques," NASA TM X-73535, Nov. 1976.
6. Huff, R. G., Clark, B. J., and Dorsch, R. G., "Interim Prediction Method for Low Frequency Core Engine Noise," NASA TM X-71627, Nov. 1974.
7. Pridmore-Brown, D. C., "Sound Propagation in a Fluid Flowing Through an Attenuating Duct," Journal of Fluid Mechanics, Vol. 4, Aug. 1958, pp. 393-406.

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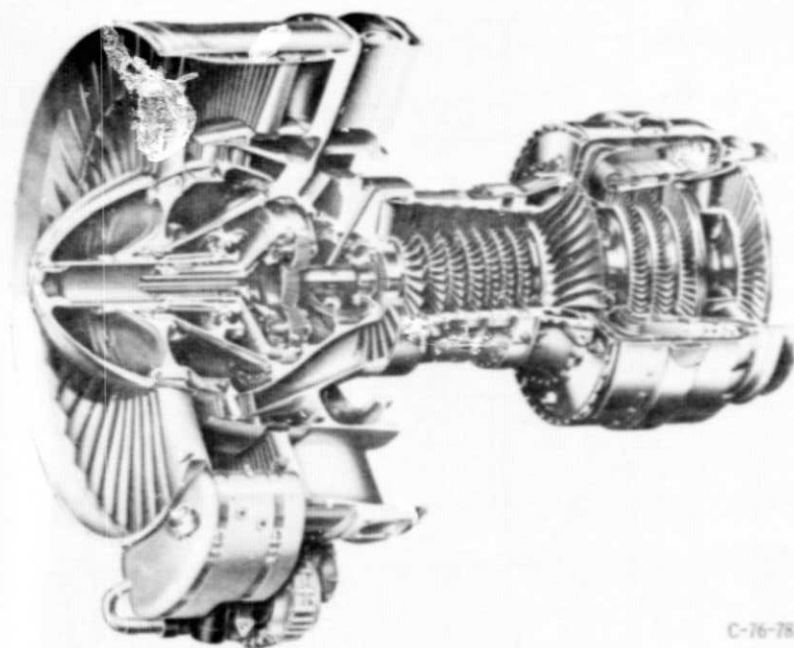
TABLE I. - TEST CONDITIONS FOR THE YF-102 CORE NOISE MEASUREMENT PROGRAM

Nominal engine speed, %	Fan speed, rpm	Core speed, rpm	Compressor Exit		Combustor		Core nozzle	
			Pres- sure, kPa	Tempera- ture, K	Pres- sure, kPa	Tempera- ture, K	Pres- sure, kPa	Tempera- ture, K
30	2335	11545	258	395	250	776	100	657
37	2795	12665	312	420	303	851	101	643
43	3260	13725	374	444	363	883	104	636
50	3790	14415	447	472	434	899	105	638
60	4540	15805	555	503	538	961	108	673
75	5695	17055	756	551	733	1124	113	774
85	6500	17935	922	585	894	1241	119	850
95	7215	18640	1097	617	1064	1353	128	906



(a) ENGINE ON STAND.

Figure 1. - YF-102 turbofan engine.



(b) CUTAWAY OF ENGINE.

Figure 1. - Concluded.

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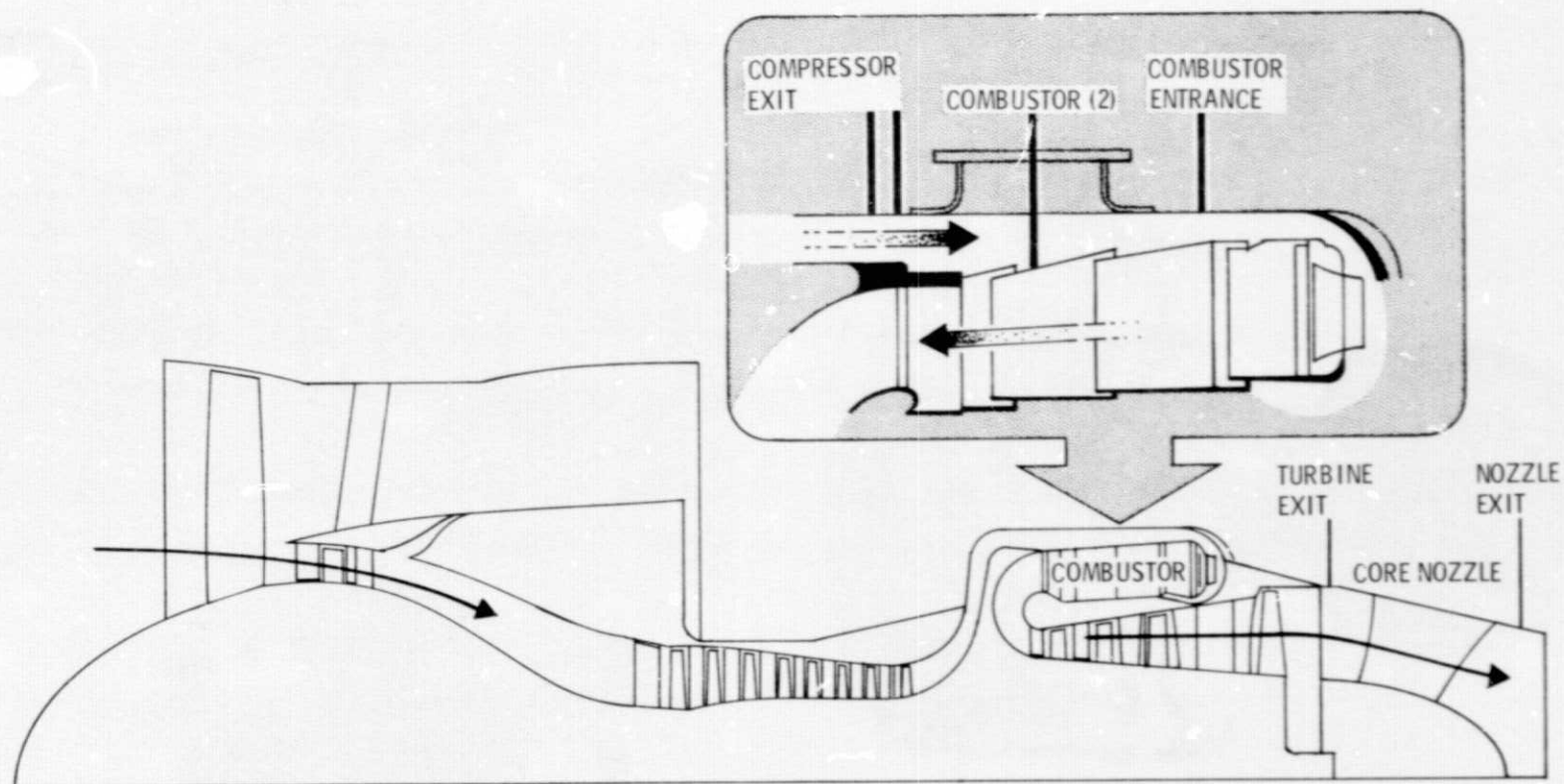


Figure 2. - Core pressure probe locations.

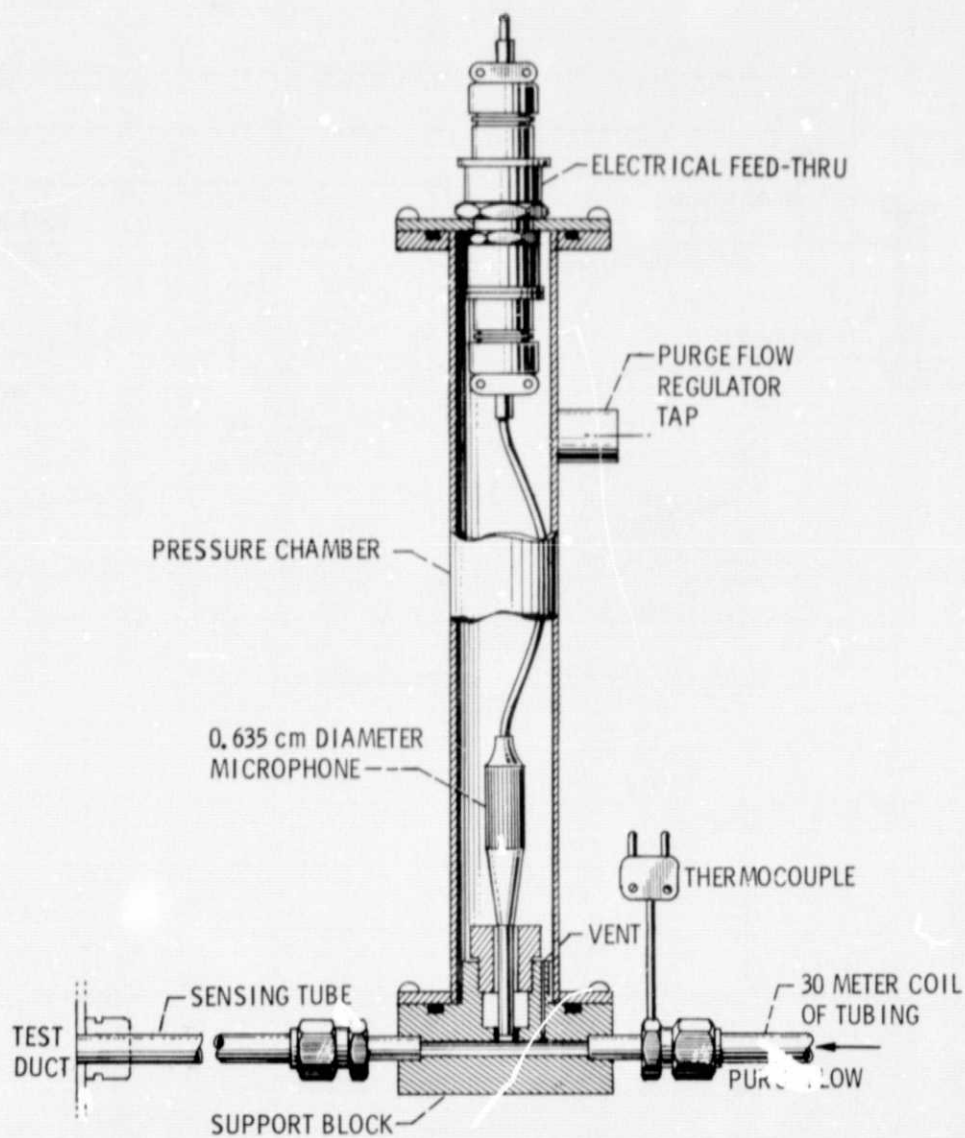


Figure 3. - Core pressure probe.

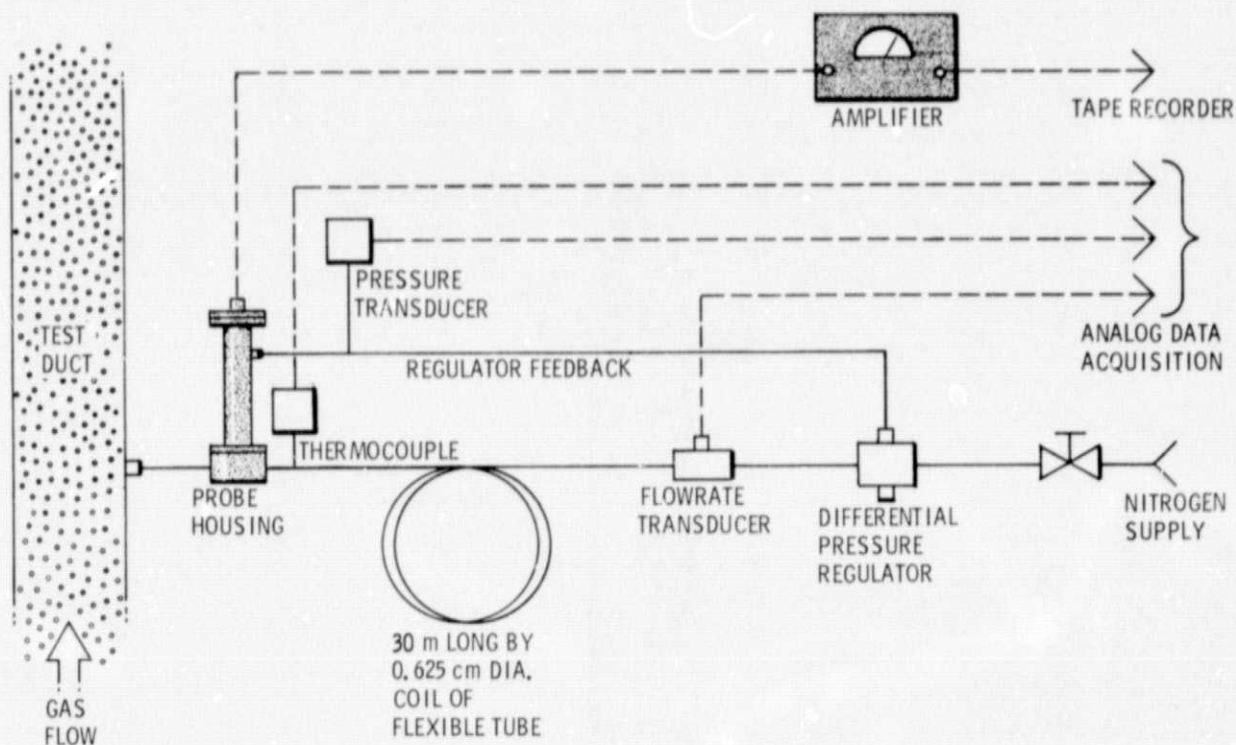


Figure 4. - Schematic of core probe installation.

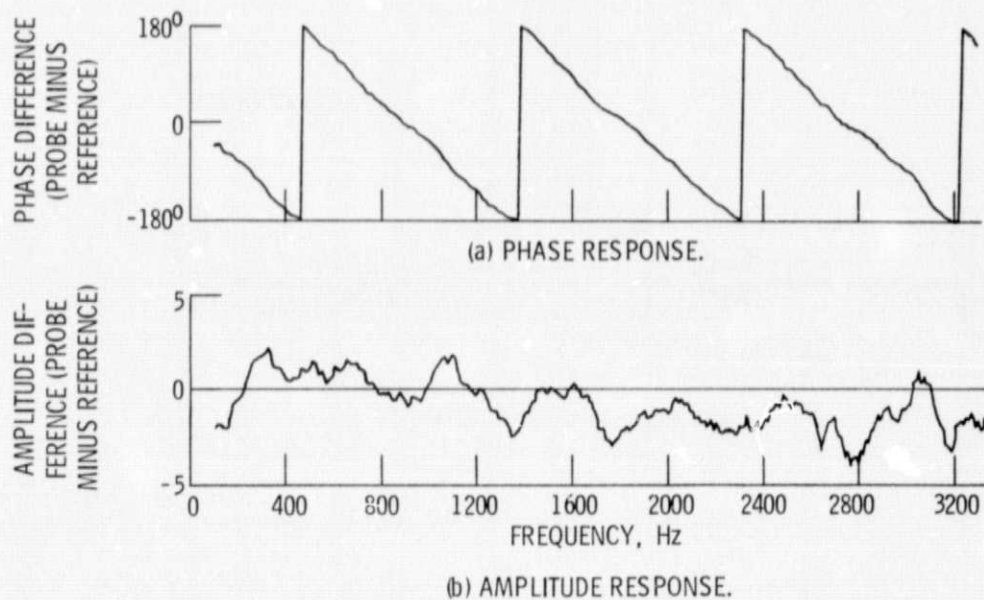


Figure 5. - Frequency response for a typical acoustic waveguide probe.

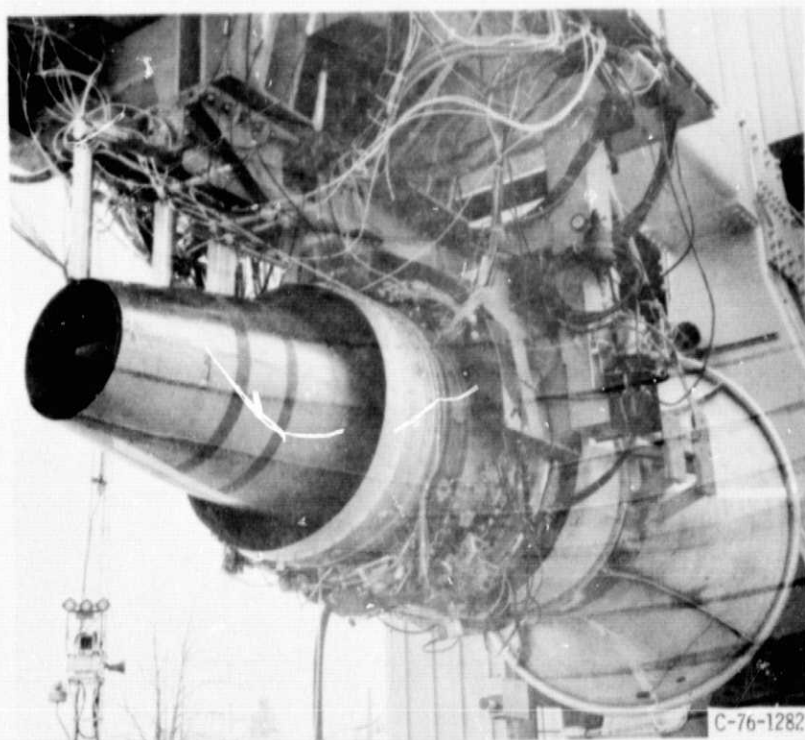


Figure 6. - YF-102 turbofan engine with mounted probes.

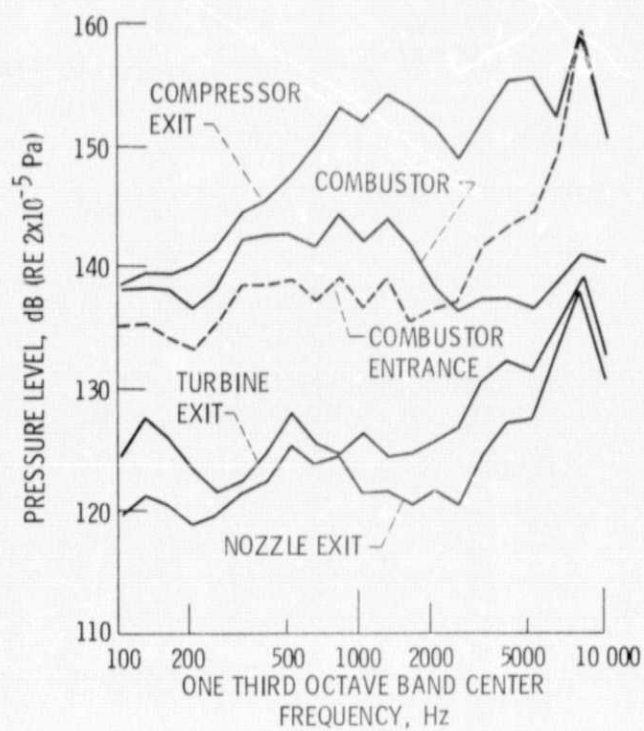
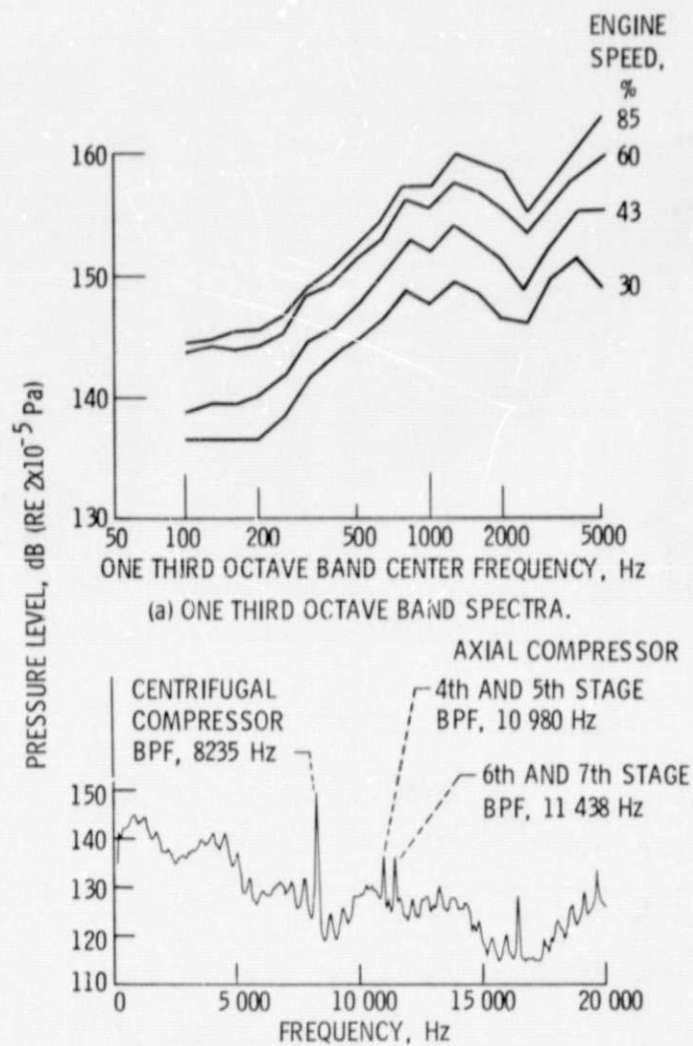


Figure 7. - Typical internal pressure level spectra. Engine speed, 43%.



(b) NARROW BAND SPECTRUM. ENGINE SPEED, 43%; FILTER BANDWIDTH, 60 Hz.

Figure 8. - Compressor exit pressure spectra.

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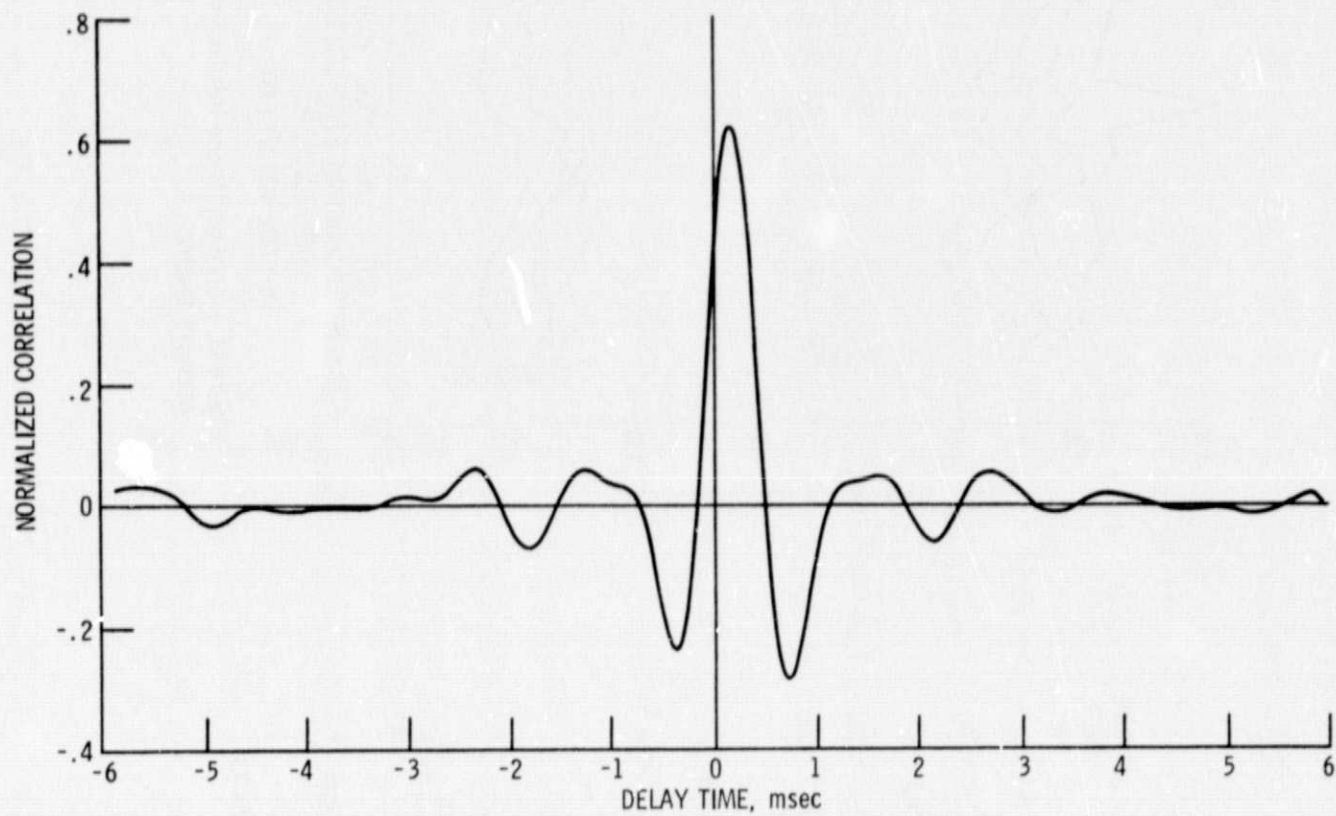
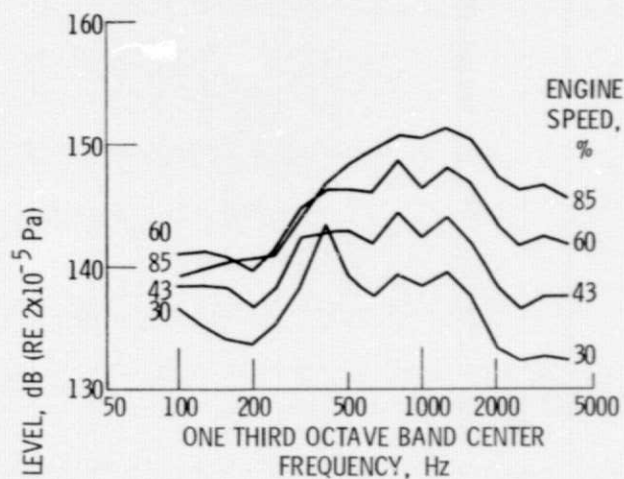
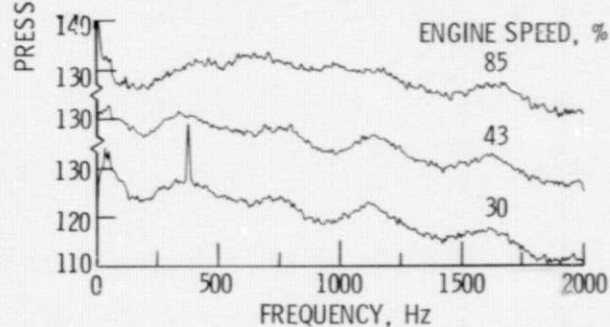


Figure 9. - Cross-correlation between compressor exit probes. Engine speed, 43%; data low pass filtered at 2000 Hz.

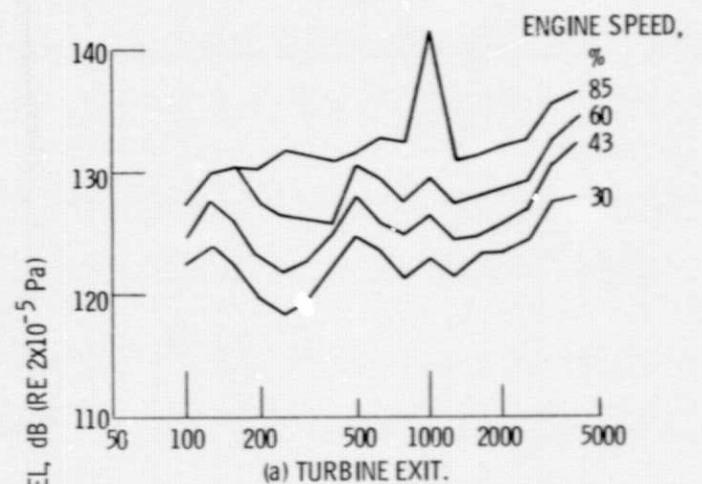


(a) ONE THIRD OCTAVE BAND SPECTRA.

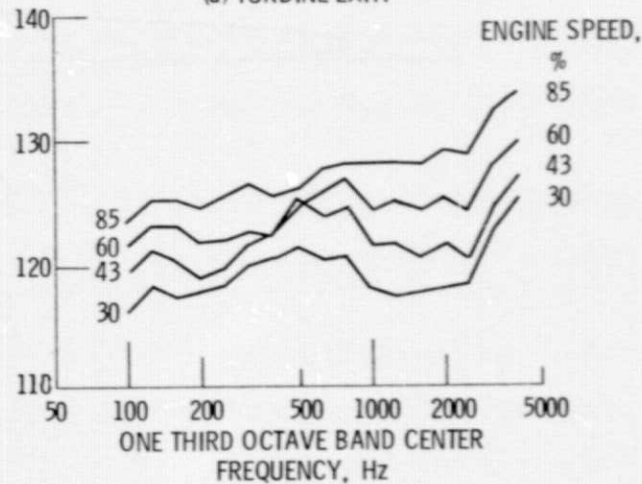


(b) NARROW BAND SPECTRA. FILTER BANDWIDTH, 6 Hz.

Figure 10. - Combustor pressure spectra.



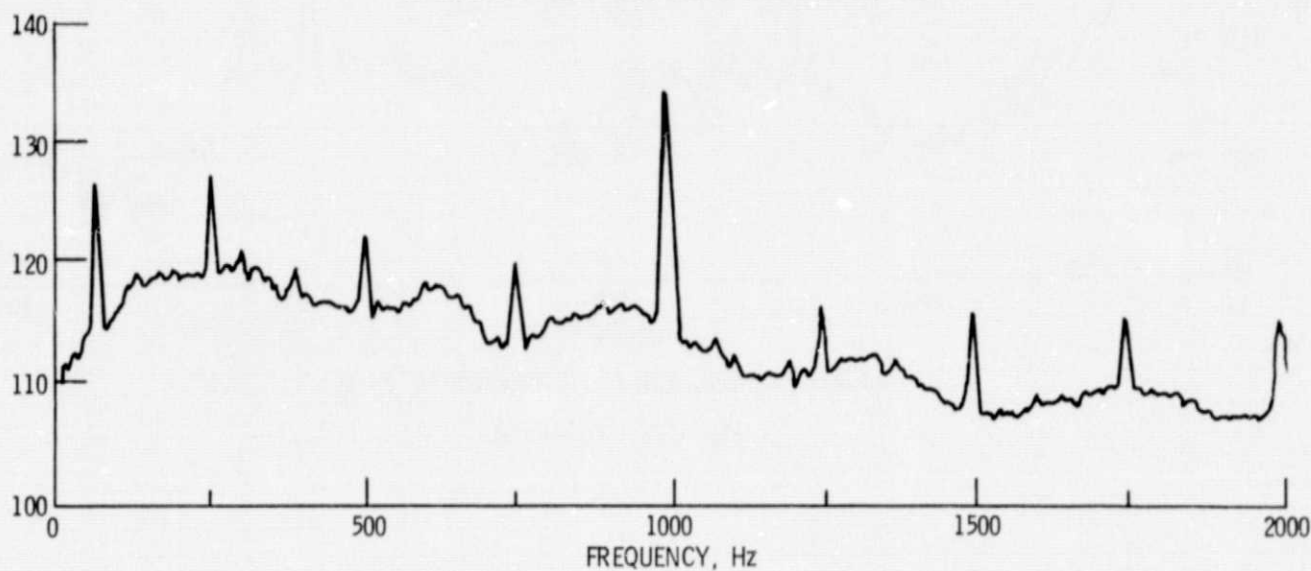
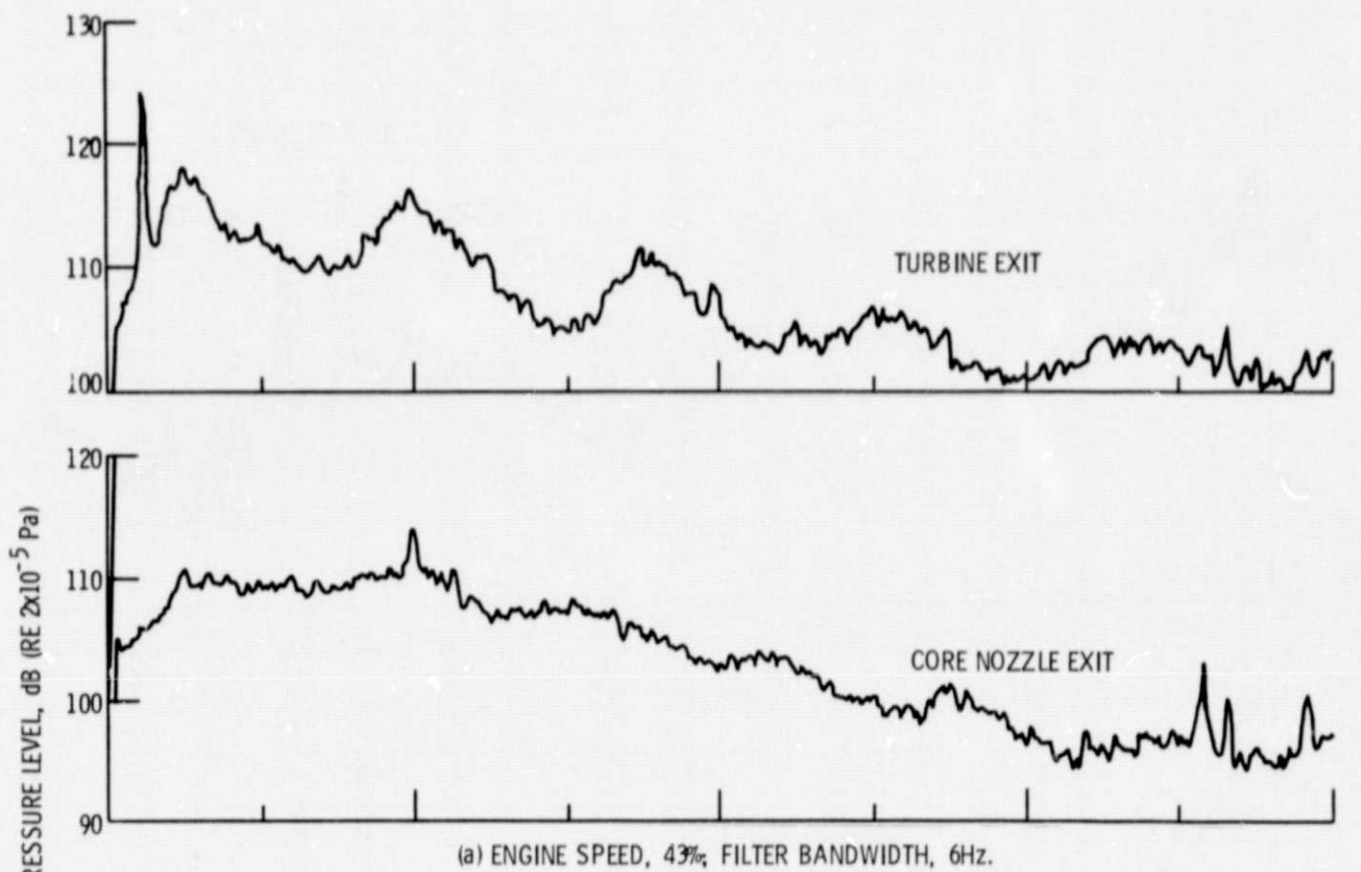
(a) TURBINE EXIT.



(b) CORE NOZZLE EXIT.

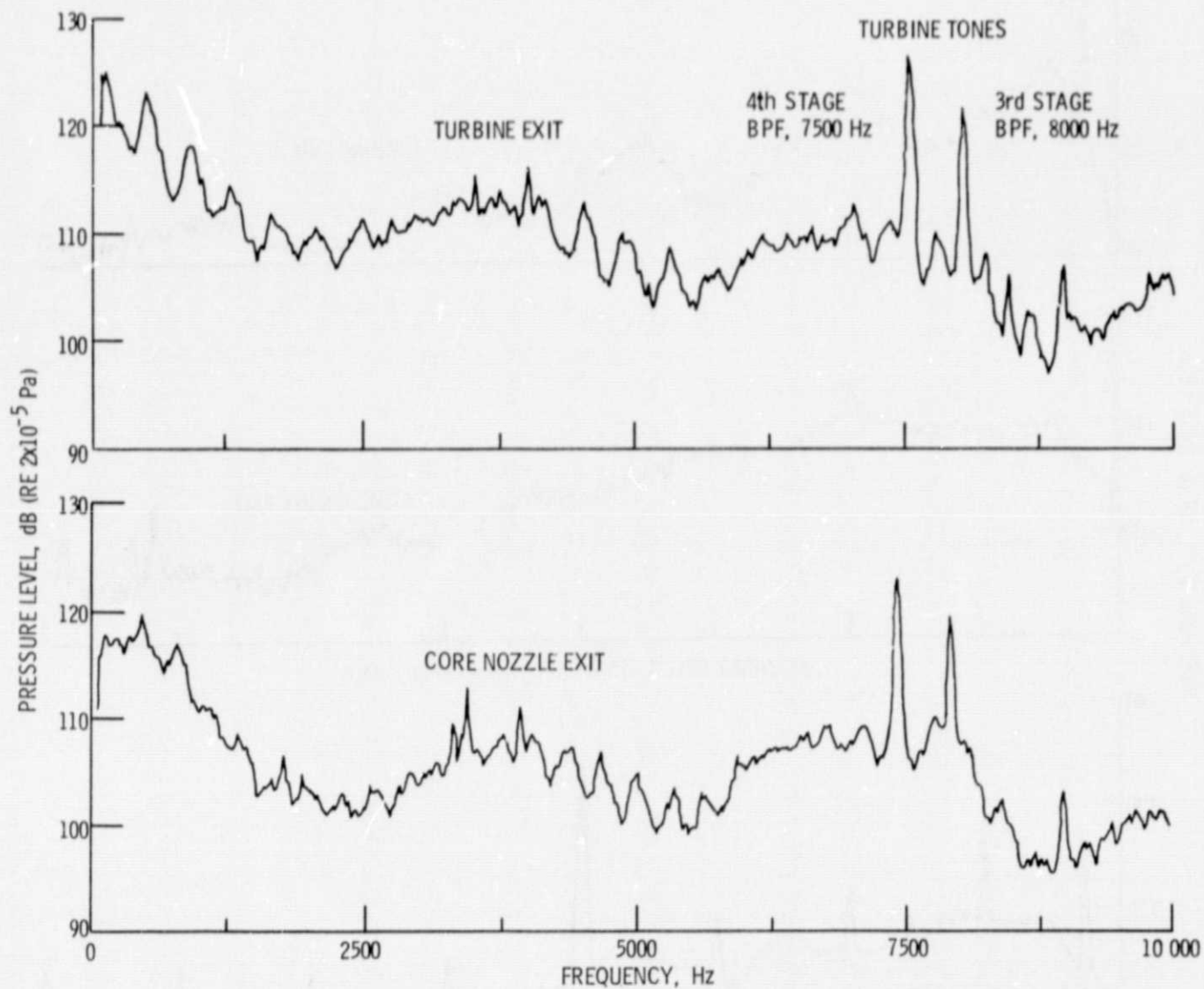
Figure 11. - Core nozzle one-third octave band pressure spectra.

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(b) TURBINE EXIT. ENGINE SPEED, 85%; FILTER BANDWIDTH, 6 Hz.

Figure 12. - Core nozzle narrow band pressure spectra.



(c) ENGINE SPEED, 43%, FILTER BANDWIDTH, 30 Hz.

Figure 12. - Concluded.

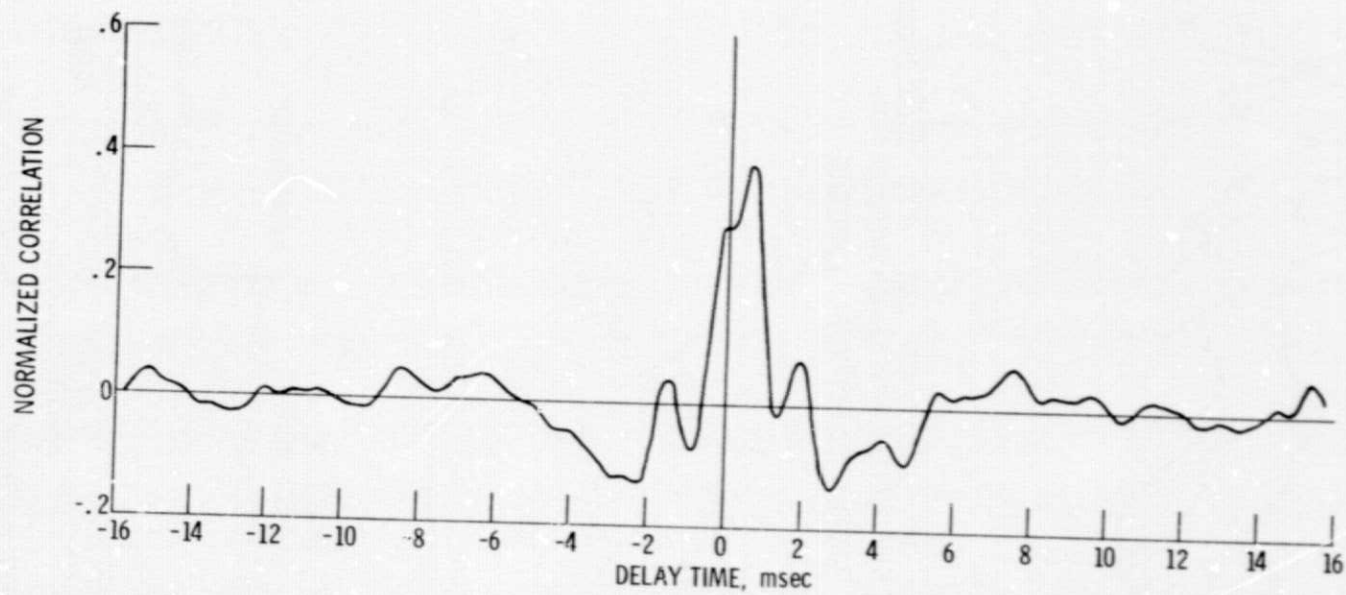


Figure 13. - Cross correlation between turbine exit and core nozzle exit pressures. Engine speed, 43%; data low-pass filtered at 1600 Hz.

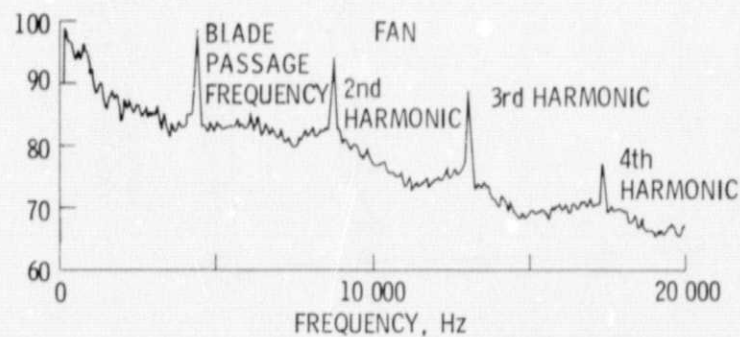
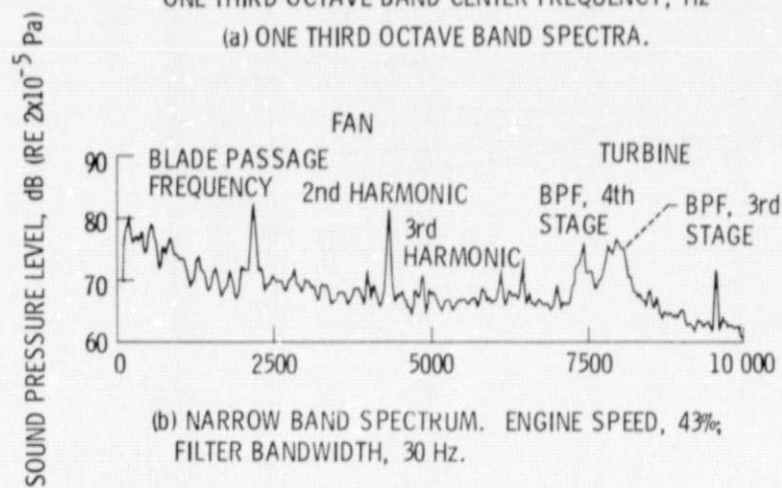
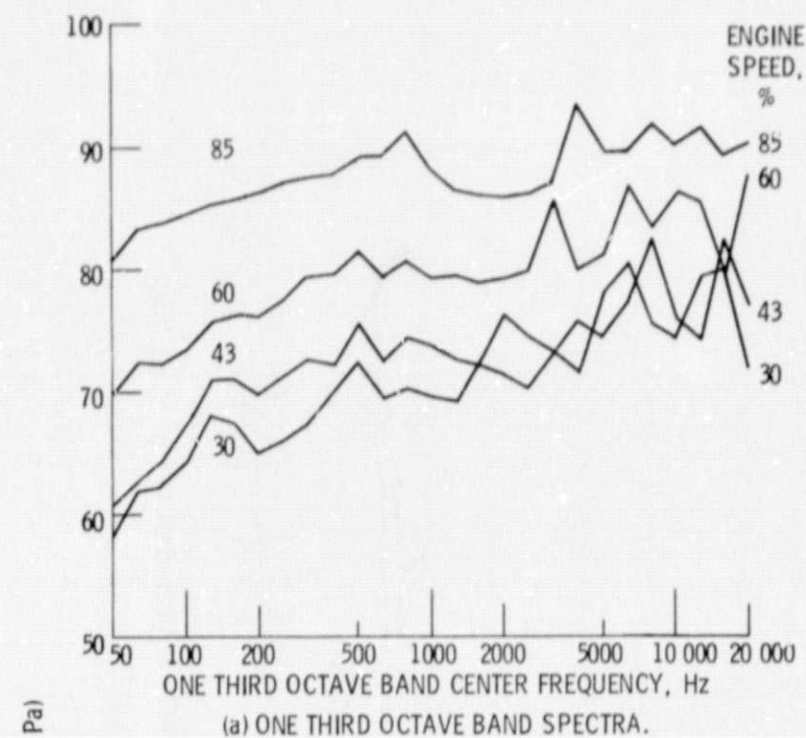


Figure 14. - Far field acoustic spectra. Distance, 30.5 m; angle from engine inlet axis, 120° .

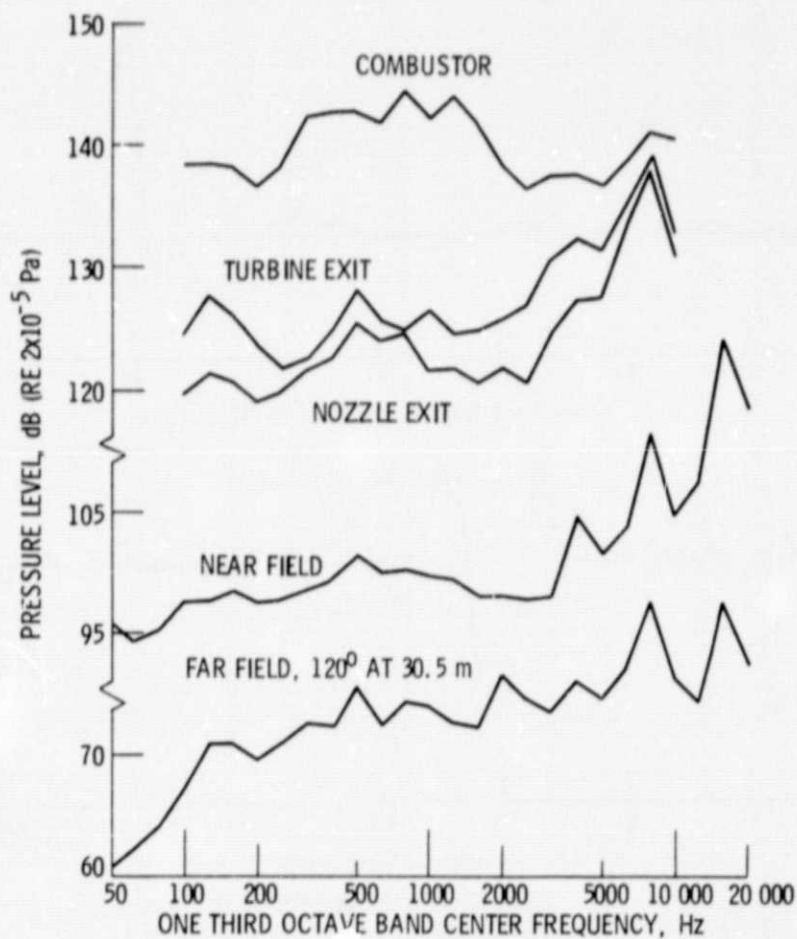


Figure 15. - YF102 internal and external pressure level spectra. Engine speed, 43%.

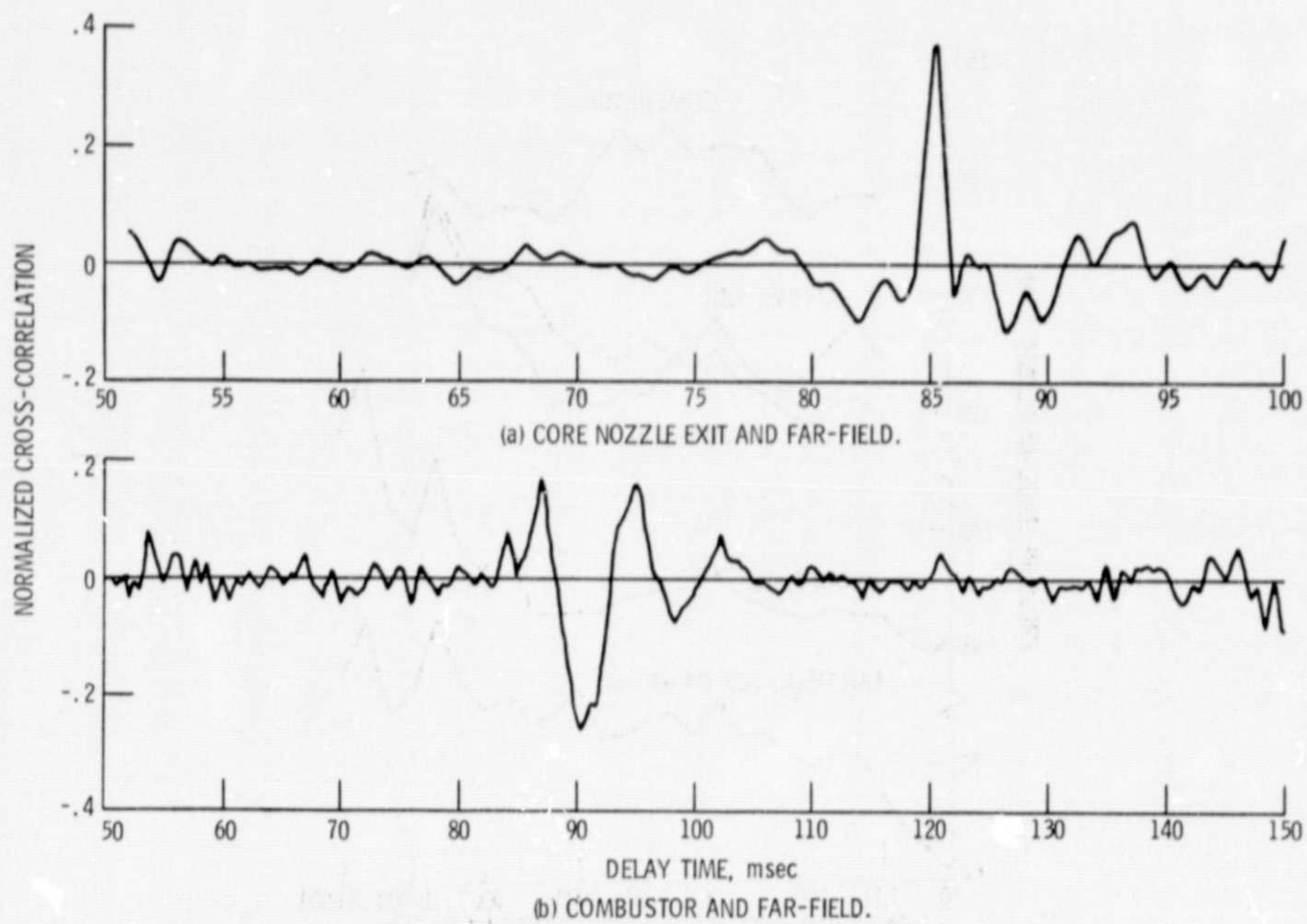


Figure 16. - Cross-correlation between internal and external signals. Engine speed 43%, data low-pass filtered at 1600 Hz.

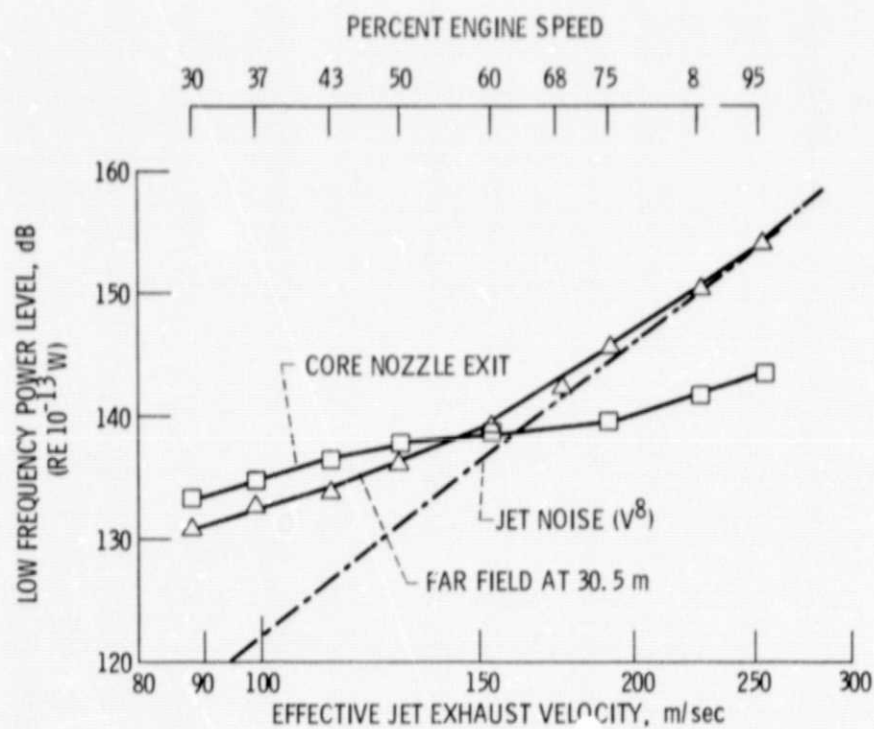


Figure 17. - YF-102 low frequency acoustic power. Frequency range, 50 to 2000 Hz.