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by Meyer Reshotko and Allen Karchmer
Lewis Research Center
Cleveland, Ohio 44135

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by Meyer Reshotko and Allen Karchmer

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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ABSTRACT

As part of a program to investigate combustor noise, simultaneous measurements were made with a YF-102 engine of combustor internal fluctuating pressure and far-field noise. From this portion of the program, the relationship of far-field noise to engine internal measurement was ascertained. Combustor internal measurements, however, are more easily obtained in duct-component rig test facilities. Consequently, the relationships between combustor internal measurements obtained in an engine and those obtained in a component test facility must be established. To explore these relationships, a YF-102 combustor, instrumented identically with that used in the engine tests, was operated in a component test facility over a range of conditions encompassing engine operation. A comparison of the directly-measured spectra at corresponding locations in the two tests shows significant differences. However, the results of two-point signal analyses within each combustor, such as coherence function, transfer function, and phase relationships, are similar for both tests. This indicates that the internal dynamics of the combustor as an acoustic source are preserved in a component test facility.

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INTRODUCTION

In the past several years considerable progress has been made in reducing the noise generated by aircraft gas turbine engines. The two largest sources of engine noise, the fan and the jet exhaust, can be reduced sufficiently to enable current aircraft to comply with federal noise regulations. Further treatment of these sources may not reduce the overall engine noise because an acoustic threshold has been reached. This threshold level is composed of noise generated from heretofore poorly understood sources within the engine core. One of the most likely sources of far field noise originating from the engine core is the combustion process where large amounts of chemical energy are released.

At the NASA Lewis Research Center, an extensive program is being conducted to determine the sources and characteristics of combustion noise and its propagation through the engine core to the far field. In part, the experimental phase of this program is being conducted with a Lycoming YF-102 turbofan engine (Ref. 1). Results obtained from direct internal and external spectral measurements indicate that below a certain condition (60% of maximum fan speed for this engine) the low frequency core noise contributes significantly to the far field noise (Ref. 1). Furthermore, it has been shown by use of correlation and coherence techniques that the combustor is the source of the low frequency core noise (Refs. 2 and 3).

It is therefore necessary to study the problem of combustion noise from turbofan engines and to develop techniques for its suppression. However, extensive testing of many combustor designs and suppression techniques on full scale turbofan engines becomes unnecessarily cumbersome and expensive. Consequently, it would be desirable to conduct such studies on less expensive test facilities specifically designed for such purposes, for example, combustor component duct rigs. An important question then arises as to the relationships between combustor internal measurements obtained in an engine and those obtained in a combustor component test facility.

To explore these relationships, a YF-102 combustor, instrumented identically to that of the engine tests, was operated in a component test facility over a range of conditions encompassing engine operation. This paper presents some of the results from these tests and preliminary comparisons of engine and test facility data.

TEST FACILITY, INSTRUMENTATION, AND DATA PROCESSING

The test program was conducted both on an AVCO-Lycoming YF-102 turbofan engine and in a component test facility. The engine, which has a bypass ratio of 6 and a rated thrust of 33 kN, was operated at an outdoor acoustic test site at the NASA-Lewis Research Center. A description of the engine and the test program may be found in Ref. 1.

Component Test Facility and Combustor

The combustor component test facility was operated for the NASA Lewis Research Center, under contract, by the Lycoming Division of the AVCO Corporation at their manufacturing and research facilities in Stratford, Connecticut. The facility, shown schematically in Fig. 1, consists of: an inlet section to distribute the flow; the combustor containing the liner, fuel nozzles, and igniters; a water cooled exhaust diffuser and plenum; an exhaust valve; and an exhaust stack to the atmosphere. Pressurized air was supplied to the facility by a series of compressors, and the desired inlet temperatures were obtained by electric heaters. Combustor inlet pressure, temperature, and mass flow rate were set to simulate engine operating conditions at the desired test points.

The YF-102 combustor, used both in the engine and component test facility, is of the annular type employing reverse flow as shown in Fig. 2. The air passes through the compressor discharge, over the combustor liner, and reverses direction. During the reversal, approximately twenty percent of the air flows through the fuel nozzle swirl vanes, while the remaining air flows into the combustor through slots and holes provided in the liner. As the flame and very hot gases move downstream, they are diluted, cooled, and mixed with the air from the liner. The hot gas is reversed again in direction, diffused and exhausted.

Measurements were made in the test facility at five conditions which corresponded to those obtained with engine fan speeds between 30% and 60% of maximum design speed (7600 rpm). A summary of the test conditions including pressure, temperatures, air and combustor fuel flow are presented in Table I. However, the results from only a single operating condition (43% speed) are reported herein, because they are considered representative of the data taken over the range of operating conditions in Table I.

Internal Probes

Dynamic pressure probes were placed in the combustor at five different locations shown in Fig. 3 as follows: two at the compressor discharge about 2 cm apart, one at the combustor entrance, and two within the combustor lines at the same axial location but separated 90^{o} circumferentially. In addition to these combustor probes, which were located in the same positions as in the engine test of Ref. 1, a sixth probe was placed in a spacer downstream of the exhaust duct (Fig. 1). However, to minimize the effects of entrance and exit differences between the two tests, this paper will only report the results obtained from the two probes within the combustor liner.

The transducers used were conventional 0.625 cm diameter pressure response condenser microphones. To avoid direct exposure of the microphones to the severe environment within the combustor, they were mounted outside and the fluctuating pressure in the combustor was communicated to the transducers by "semi-infinite" acoustic waveguides.

A drawing of a typical acoustic waveguide probe is shown in Fig. 4. 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 between the pressure chamber and sensing line. A schematic diagram of a typical combustor probe installation is shown in Fig. 5.

Ambient temperature calibration tests of these probes indicated a flat frequency response within ±2 dB and a phase response of $\pm 5^{o}$ up to 1500 Hz. Additional details on these probes are contained in Ref. 1.

Data Acquisition and Processing

The signals from the internal probes were FM-recorded on magnetic tape in two or five minute record lengths for later processing. The probes were calibrated with a pistonphone before and after each day's running.

The results given in this paper were obtained by off-line processing of the tape-recorded data on a two-channel fast Fourier transform digital signal processor with built-in analog to digital converters and 120 dB/octave anti-aliasing filters. The processor was capable of direct computation of up to 4096 ensemble averages of a 1024 point forward or inverse Fourier transform to yield either frequency domain (coherence, amplitude and phase spectra, and transfer function) or time domain (correlation) information.

RESULTS AND DISCUSSION

Spectra

One-third octave band and constant bandwidth spectrum analyses of the dynamic pressure measurements take within the combustor on both the component test facility and the engine are shown in Fig. 6. As indicated previously, all data presented herein were obtained at a condition corresponding to 43% of maximum engine speed (Table I). The 1/3 octave band data (Fig. 6(a)) were corrected for frequency response of the probes and for ambient pressure (Ref. 1), while the constant bandwidth spectra are presented without corrections. The pressure level spectra in Figs. 6(a) and (b) include frequencies up to 2000 Hz. (The frequency range of combustion noise generated by turbofan engines is generally agreed to occur below 2000 Hz.) In broad terms, the comparison between component test facility and engine spectra shows fair agreement above 500 Hz and poorer agreement below. Constant bandwidth analysis up to only 500 Hz is shown in Fig. 6(c). In this frequency range, the test facility and engine spectra differ in level at almost all frequencies and the shapes differ below 200 Hz. The dynamic pressure levels measured in the component test facility, at frequencies above 100 Hz, are approximately 5 dB above those measured in the engine.

The realtively poor agreement of single point measurements (spectra) made in the component test facility and in the engine for identical combustors, probe locations, and gas properties within the combustor could mean, either, that there is no relationship between engine and component rig measurements, or, that there may be many other phenomena taking place which obscure this relationship. Although the geometry and thermodynamic operating conditions entering and within the combustor are the same for both cases, the upstream and downstream conditions are not. In the engine, flow enters the combustor immediately from a centrifugal compressor stage (Ref. 1) and in the rig it enters from a supply duct (Fig. 1). The turbulence characteristics of the incoming flows and the acoustic impedance of the entrances are believed to be significantly different and may have a strong effect on the spectra generated. At the combustor exit in the engine, flow enters a four stage turbine and a plug nozzle before exhausting to the atmosphere (Ref. 1); but on the test facility, it passes through an exhaust diffuser, plenum, and butterfly valve (Fig. 1). These two different exit conditions may also cause large differences in resonance. These and other differences may consequently cause large discrepancies between the single point measurements (spectra) made in the combustor.

Two-Point Data Analyses

In order to help better understand the dynamic pressure characteristics within the combustor, two point coherence and correlation functions have been used (Refs. 2 and 3) between the internal and far field engine measurements, and between pairs of internal measurements. Similar measurements have been made for the combustor component rig tests.

Coherence functions. - The coherence function is essentially a normalized cross-spectrum and is defined for random signals as (Ref. 4)

$$\gamma_{ab}^2(f) = \frac{|G_{ab}(j\omega)|^2}{G_{aa}(\omega)\, G_{bb}(\omega)} \qquad \omega = 2\pi f,\ j = \sqrt{-1}$$

where $|G_{ab}(j\omega)|^2$ is the square of the ensemble averaged cross-spectral density between a and b; and $G_{aa}(\omega)$ and $G_{bb}(\omega)$ are the averaged autospectral densities at a and b, respectively. The coherence function must have a value between zero and one, with high coherence at a particular frequency, f, meaning high correlation at that frequency.

Herein, the coherence function will be used primarily to describe the frequency characteristics of the fluctuating pressure within the YF-102 combustor. The magnitude of the coherence function will be referred to in relative terms and will be used mainly for comparison purposes between test facility and engine data.

The coherence function between two pressure probes within the combustor 90° apart, installed in the component test facility, is shown in Fig. 7. Although data were analyzed up to 2000 Hz, the coherence is essentially negligible above 1000 Hz. Below 1000 Hz there are two separate and distinct regions of coherence: the first between zero and 400 Hz; and the second between 600 and 1000 Hz. In the first region, there is a well-defined peak at 120 Hz. This corresponds to the peak frequency of combustion associated noise which propagates to the far field as measured on the YF-102 engine (Refs. 2 and 3). There is also a secondary, smaller peak at approximately 200 Hz in this same region. It is believed that this is due to a resonance of the test facility plenum. Considering the length of the plenum, and the damping factors caused by the upstream diffuser and partially opened downstream butterfly valve, which are at the opposite ends of the plenum, the resonance frequency is calculated to be approximately 200 Hz (Ref. 5). Conceivably, if one could remove the resonance phenomenon, the first region of coherence could go to zero at approximately 250 Hz (instead of 400 Hz as indicated in Fig. 7).

In Ref. 2 it has been shown for the YF-102 engine that combustion associated noise propagates to the far field, but its contribution is limited to frequencies below 250 Hz. In the present study, the combustor coherence measurements fall into two regions: a low frequency region which corresponds to the region of far-field noise propagation for the engine, and a high frequency region (600 to 1000 Hz), shown in Fig. 7, which does not propagate to the far field.

A comparison between combustor coherence measurements from the component test facility (Fig. 7) and from the engine is presented in Fig. 8. For the engine data there are also two separate regions of coherence, and again the coherence is virtually zero above 1000 Hz. In the second region of coherence, from 600 to 1000 Hz, the lower and upper frequency limits are the same for both rig and engine data with a slight increase in peak frequency for the engine data. In the low frequency region, the engine data appears to reach a peak coherence at 60 Hz, which is due to electrical noise. However, even after taking this into account, there is still a large discrepancy between rig and engine data up to 120 Hz. Between 120 and 200 Hz, the data are in very close agreement, and between 200 and 400 Hz the results disagree only because of the assumed presence of duct resonance in the test facility. In summary, there is good agreement between combustor coherence measurements made both in an engine and component test facility at frequencies above 120 Hz after the facility resonance is discounted.

Cross-correlation. - It is of interest to examine the cross-correlation function using the coherence measurements of Fig. 8 as a guide for filtering the data. The measured cross-correlation between the filtered fluctuating pressure signals from the two combustor probes are shown in Fig. 9. In Fig. 9(a), the signals have been low pass filtered at 400 Hz, the upper limit of the first region of coherence in Fig. 8. The resulting correlation is an evenly symmetric function with respect to a positive peak at a delay time of zero. In Fig. 9(b) the signals have been band-pass filtered between 400 and 1200 Hz to include only the second region of coherence (600 to 1000 Hz). This correlation is significantly different in shape from the previous one. Although still symmetric, it contains two positive peaks and a negative peak (of symmetry) about a delay time of zero.

Phase shift. - The shape of the correlation function (time domain) is determined by the phase and amplitude relationships (frequency domain) between the two signals. The phase shift between the two combustor signals, for both engine and component test facility, is shown in Fig. 10 for all frequencies up to 1200 Hz. Again, there are two frequency ranges where the test facility and engine data are in good agreement. Up to a frequency of 250 Hz both sets of data have a phase shift of zero degrees, and between 600 and 950 Hz there is a phase shift of 180^{o}. At all other frequencies the phase shift appears to be of a random nature.

Transfer functions. - The amplitude relationship between the two combustor signals, for component test facility and engine, as represented by the transfer function is shown in Fig. 11. In the present context, the transfer function between the two signals is the ratio of the amplitude of the cross-spectrum to the amplitude of the auto-spectrum of a given combustor signal. In the frequency ranges from 120 to 300 Hz and from

600 to 1000 Hz there is qualitative agreement between the two sets of data. The magnitudes of the transfer functions in these frequency ranges differ by a few dB and their shapes are similar. Between 0 and 120 Hz the comparison is poor, and between 400 and 600 Hz, which corresponds to the region of zero coherence (Fig. 8), the transfer functions are random in nature.

Discussion

In the present study, although an identical combustor with identical operating conditions was used in both cases, the combustion related spectra did not reproduce well. This could be due to: altered combustor fluctuating pressure generation, contamination of the measured signal by extraneous resonance or other signals introduced by the test rig, or by a combination of these. However, because the results obtained with the two-point measurements were similar in both cases, it is reasonable to discount rig-generated acoustic contamination as the problem. Such a phenomenon would be expected to result in different two-point characteristics.

The invariance of the two-point measurements implies that the internal dynamics of the combustor fluctuating pressure as a source are preserved. This finding in the face of the spectral differences suggests that the combustor is preserving its internal pressure behavior as an acoustic source, but that in each facility it is being subjected to different boundary conditions. This implies that the combustor entrance and exit conditions, which were not duplicated in each case, are important. In summary, different inputs (combustor entrance and exit conditions) result in different outputs (combustor pressure spectra) but the generating mechanisms remain the same as evidenced by the two-point measurements.

In order to insure that the results obtained from the two-point signal analysis measurements are due primarily to the combustion process, the tests were repeated with no burning (zero fuel-flow) in the combustor. The results indicate that at all frequencies above 30 Hz the coherence and cross-correlation functions are zero.

It should be emphasized that although the results from only a single operating condition are discussed in this paper, data for the other conditions listed in Table I were examined and the results were similar.

CONCLUDING REMARKS

In order to determine the relationships between combustor internal measurements obtained in an engine and in a component test facility, an instrumented YF-102 combustor was tested in both environments over a common range of operating conditions and a comparison of measured data was made. The single point measurements, spectral data, show good agreement above 500 Hz, and poorer agreement below. Coherence measurements, between the fluctuating pressures obtained by a pair of probes within the combustor, show good agreement between engine and test rig. They indicate no coherence above 1000 Hz, and two frequency ranges of coherence below. The low frequency region of coherence corresponds to combustion-associated noise which propagates to the far field on the YF-102 engine as reported elsewhere. A comparison of phase differences between the two combustor signals, for both cases, shows agreement in regions of high coherence and random differences in regions of low coherence. Although a comparison of directly measured single point spectra in the two tests showed significant differences, the results of two-point signal analyses within each combustor indicates that the nature of acoustic source information is reproduced in a component test facility.

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5. L. L. Beranek, Noise Reduction (McGraw Hill, New York, 1960).

TABLE I. - YF-102 COMBUSTOR TEST CONDITIONS IN THE COMPONENT TEST FACILITY

Nominal engine speed, %	Compressor discharge		Combustor			
	Pressure, kPa	Temperature, K	Pressure, kPa	Temperature, K	Air flow, kg/sec	Fuel flow, kg/hr
30	258	405	240	800	4.92	179
37	312	421	293	824	5.90	221
43	374	444	354	874	6.48	261
50	447	473	420	877	8.00	306
60	555	505	520	966	9.53	423

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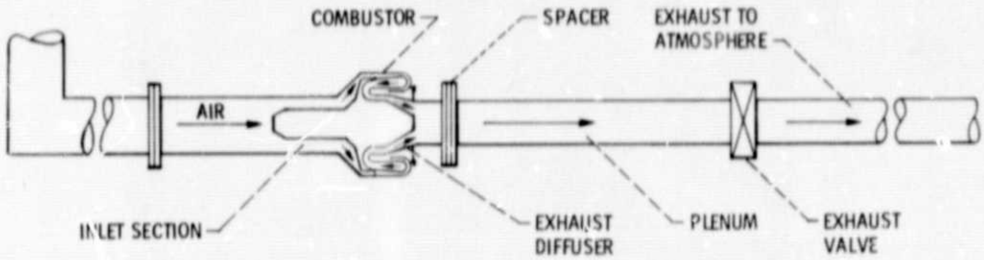

Figure 1. - Combustor component test facility.

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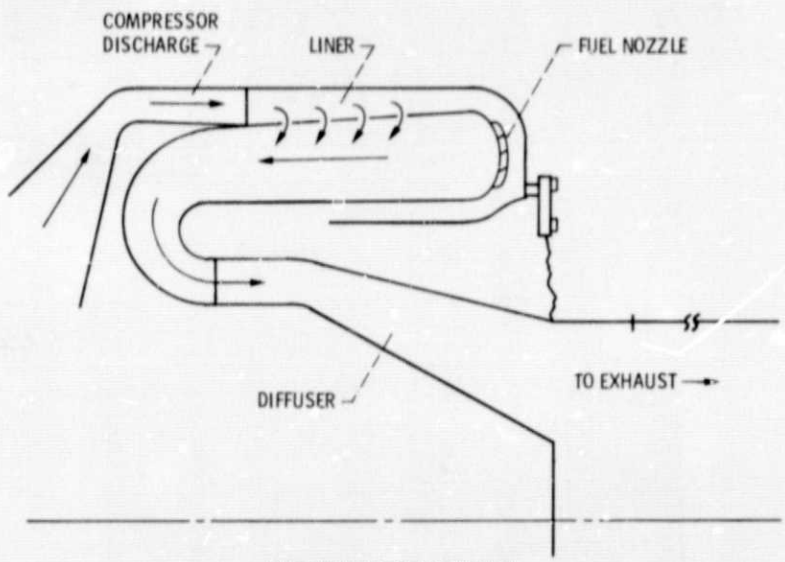

(a) SCHEMATIC OF FLOWPATH.

Figure 2. - YF-102 combustor and diffuser.

(b) PHOTOGRAPH OF COMBUSTOR AND DIFFUSER.

Figure 2. - Concluded.

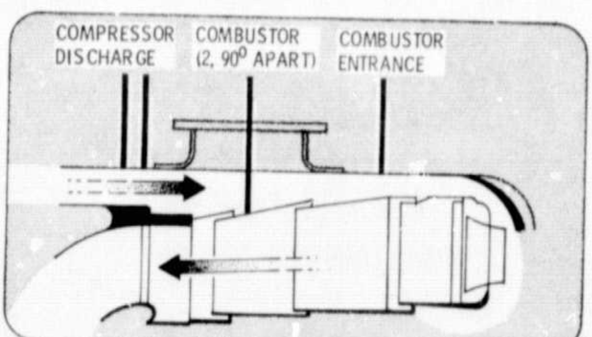

Figure 3. - Combustor pressure probe locations.

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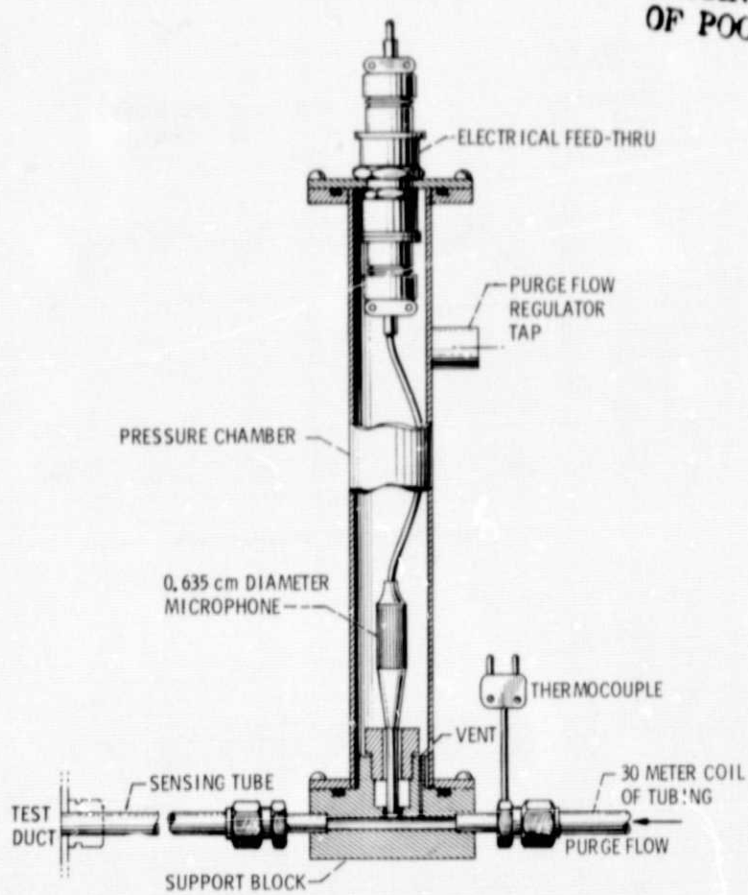

Figure 4. - Combustor pressure probe.

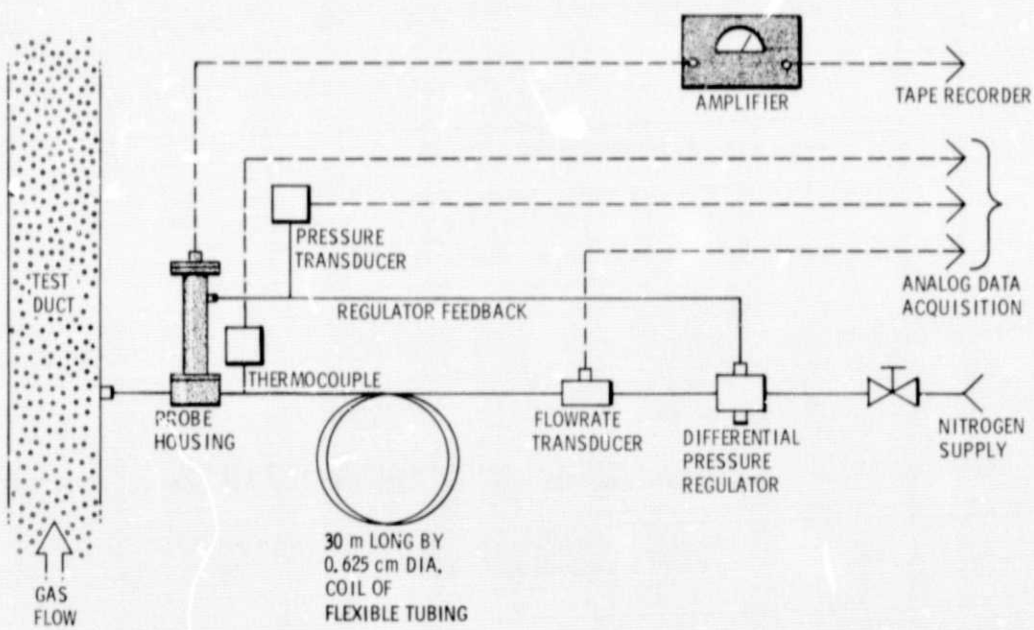

Figure 5. - Schematic of combustor probe installation.

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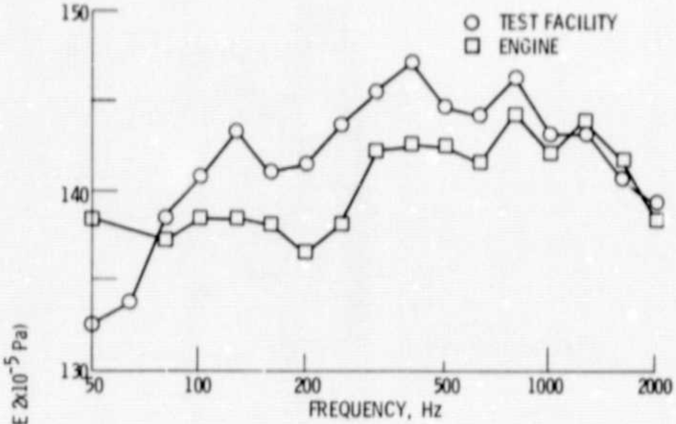
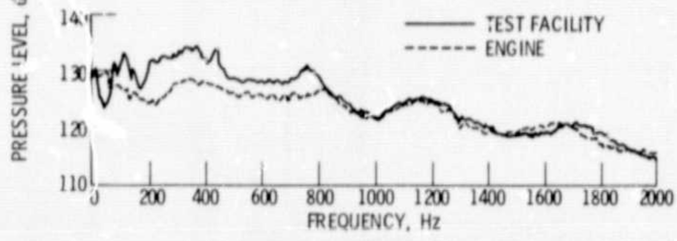
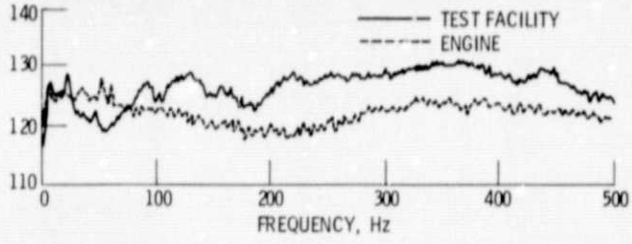


(a) ONE-THIRD OCTAVE BAND ANALYSIS.



(b) CONSTANT BANDWIDTH ANALYSIS; FILTER BANDWIDTH, 4 Hz.



(c) CONSTANT BANDWIDTH ANALYSIS; FILTER BANDWIDTH, 1 Hz.

Figure 6. - Comparison of combustor fluctuating pressure spectra in the engine and component test facility.

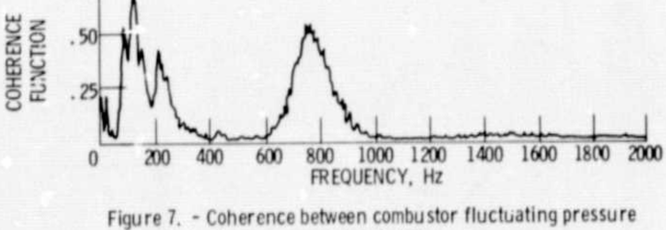


Figure 7. - Coherence between combustor fluctuating pressure signals in the component test facility.

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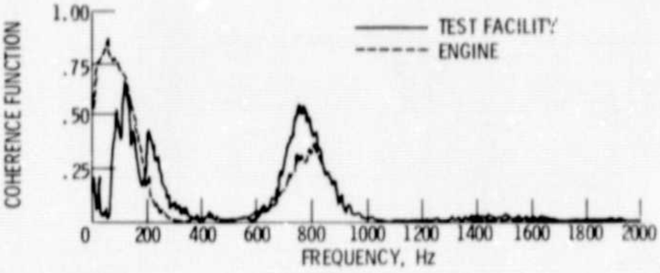

Figure 8. - Coherence between combustor fluctuating pressure signals in the engine and component test facility.

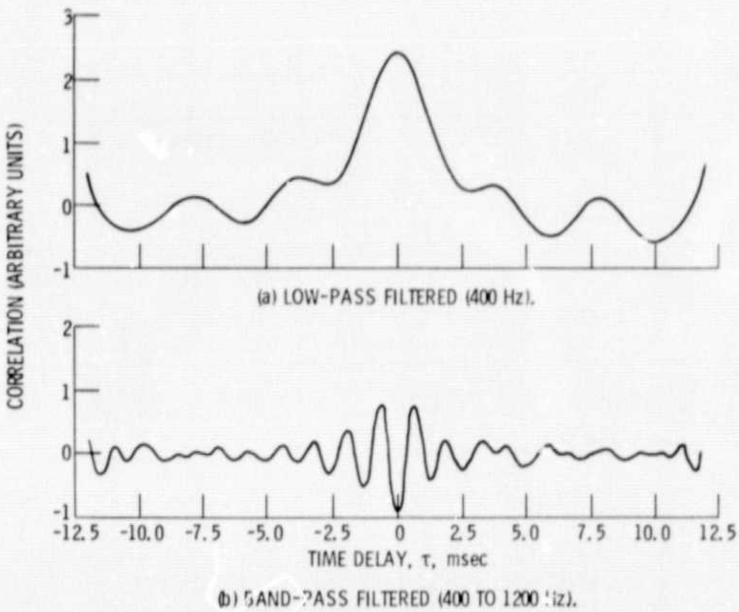

Figure 9. - Cross-correlation between combustor signals.

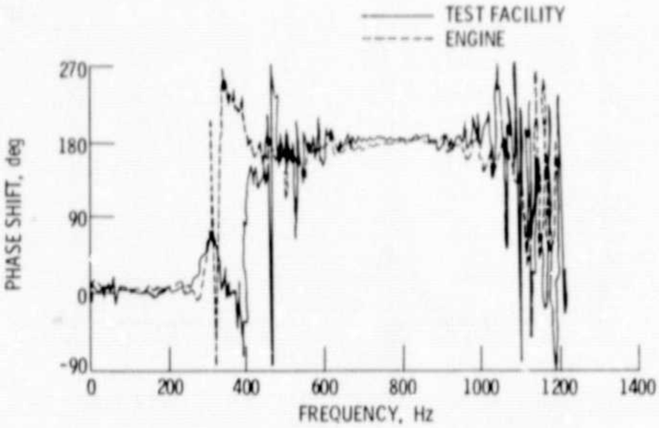

Figure 10. - Phase shift between combustor signals in the engine and component test facility.

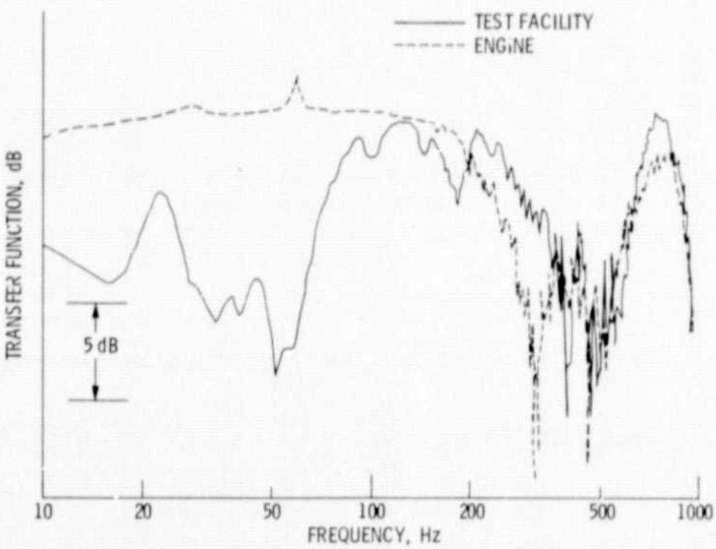

Figure 11. - Transfer function between combustor signals in the engine and component test facility.

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