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COMPARISON OF CROSS-SPECTRAL AND SIGNAL ENHANCEMENT METHODS FOR MAPPING STEADY-STATE ACOUSTIC FIELDS IN TURBOMACHINERY DUCTS

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16. Abstract

Any steady-state acoustic field can be completely specified by spatially mapping the pressure amplitude and phase as a function of position and frequency. However, in many measurement situations, the observed pressure is not due entirely to the steady-state field, but also contains random transients (either acoustic or nonacoustic). Using modern real-time analysis equipment, it is possible to measure spatial variations in steady-state acoustic pressure amplitude and phase by taking the cross spectrum between two signals from probes in the same field or by taking the difference in complex Fourier transforms of enhanced probe signals. The conceptual differences between these two approaches are examined, and each is used to analyze pressure data from the inlets of two different turbomachines. A complete mapping of this steady-state field could be used to determine its modal content. A problem with long term nonstationarity is found with both methods. Conditions for equivalence of the two methods are discussed.

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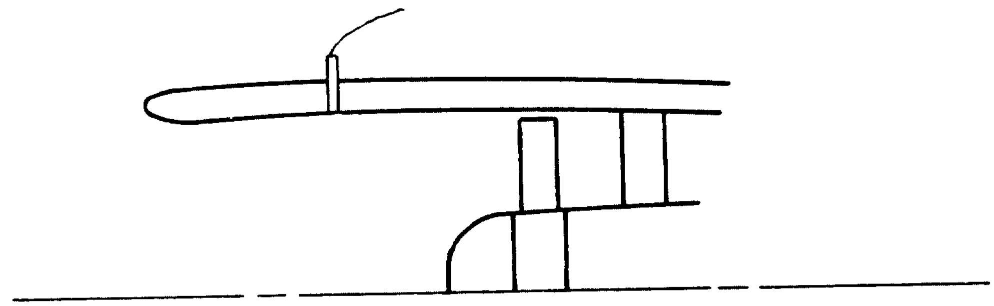
INTRODUCTION

The complexity of the acoustic field inside turbomachinery ducts during a static test has only recently become generally appreciated (refs. 1 - 5). It has become clear that significant, even dominant, contributions to the field may be made by mechanisms which are greatly reduced or even totally absent in flight. Also, theoretical studies of liner optimization (refs. 6 and 7) indicate that a complete field description (such as a tabulation of mode amplitudes and phases) is required to determine the acoustic liner design which yields the maximum attenuation. In order for such a mapping of the inflight acoustic field to be obtained from a ground test, one must have a detailed understanding of the various possible noise mechanisms and how each contributes to the noise under various test conditions.

Figure 1 lists possible sources of acoustic pressure fluctuations which could be sensed by a flush-mounted pressure transducer on the wall of a turbomachinery duct. Here attention is restricted to fluctuations at the rotor's blade passage frequency (BPF) and its overtones, so that aerodynamic pressure variations are negligible with respect to acoustic pressures. Of the acoustic mechanisms listed, steady blade loading, rotor wake/stator interaction and



STEADY STATE

STEADY BLADE LOADING
ROTOR WAKE/ STATOR INTERACTION
FIXED INFLOW DISTORTION/ ROTOR INTERACTION

NARROW BAND RANDOM

INGESTED ATMOSPHERIC TURBULENCE/ ROTOR INTERACTION
BOUNDARY LAYER/ ROTOR INTERACTION

Figure 1. Possible blade passage frequency sound sources in turbomachinery ducts.

fixed inflow distortion and rotor interaction produce steady-state, pure tone noise assuming that the shaft speed is invariant. The remaining mechanisms, ingested atmospheric turbulence/rotor interaction and boundary layer/rotor interaction were found by Hanson (ref. 3) to be strongly related, with the boundary layer fluctuations having sufficient duration to contribute to BPF noise being generated by the ingested turbulence. Since the location, size, strength, and duration of ingested turbulent eddies are all random, with durations (ref. 3) of the order of 50 to 100 shaft revolutions, these last two mechanisms do not produce steady-state acoustic disturbances, but rather narrow band random noise about the BPF due to the longer eddies and broadband random noise due to the shorter eddies. Roundhill and Schaut (ref. 5) have presented convincing empirical evidence that narrow-band random noise often dominates the BPF spectral level in ground tests of modern high bypass ratio engines, but is much less pronounced in flight measurements. They explain this by the presence of relatively long, thin eddies in the flow during static tests and their absence during flight. Thus, it would be one step closer to measuring the in-flight noise via static testing if one could measure the steady-state acoustic field while minimizing fixed inflow distortions.

A number of data analysis techniques are available to extract steady state disturbances from narrow band random noise, but two which are readily available on modern two-channel, hard-wired digital analysis equipment are the cross spectrum and signal enhancement. The cross spectrum has already been used to measure spinning modes in the inlet of a high-speed, axial-flow compressor (ref. 8).

Some of the data analyzed here was collected and furnished to the author by Mr. Keith Bekofske of the General Electric Company.

THEORY

The basic function of digital analysis equipment is the evaluation of the discrete Fourier transform, F, which is conveniently defined by the expression given in figure 2. Here x(t) is an arbitrary function of time sampled at N discrete equally spaced points on the time interval $[0,(N-1)\Delta t]$. The frequency resolution Δf of the transform F is $(N\Delta t)^{-1}$, and i is $(-1)^{1/2}$. This definition is preferred, because the real and imaginary parts of the resulting transform F are the cosine and sine series coefficients, respectively, required to recover the N samples of x. In practice, the function x(t) is low pass filtered to minimize aliasing and the samples $x(n\Delta t)$ are multiplied by a data window W(n/N) before transformation to minimize leakage from one frequency band to another. An excellent discussion of this procedure is given by Bergland (ref. 9).

The cross spectrum F_{12} of two signals x_1, x_2 sampled at the same time points and having transforms F_1, F_2, respectively, is defined (figure 2) as the product of F_2 and complex conjugate of F_1. This gives a complex number with magnitude $|F_1| \cdot |F_2|$ and phase $\phi_2 - \phi_1$. If x_1 and x_2 are both pure tone signals with frequency BPF, but different amplitudes and relative phases, then the magnitude of F_{12} is clearly given by the product of these magnitudes and its phase by the difference of the phases. On the other hand, should x_1 and x_2 both be narrowband random processes, so that both their amplitudes and their relative phases are random at frequency, BPF, then F_{12} would have random amplitude and phase and its average $\overline{F}_{12}$ over a large enough ensemble would vanish. Therefore, when F_1 and F_2 contain both steady-state and independent random (in the manner mentioned above)components, an average

DISCRETE FOURIER TRANSFORM, $\mathcal{F}$

$$\mathcal{F}\{x(t)\} = F(m\Delta f)$$

$$= \frac{1}{N} \sum_{n=0}^{N-1} x(n\Delta t) \exp(i\, 2\pi\, n\, \Delta t\, m\Delta f)$$

$$F(m\Delta f) = |F| e^{i\Phi}$$

CROSS SPECTRUM, $\tilde{F}_{12}$

$$F_{12}(m\Delta f) = F_2 \cdot F_1^*$$

$$= |F_2|\,|F_1|\, \exp\left[i(\Phi_2 - \Phi_1)\right]$$

ENHANCED SIGNAL, x^E

$x^E(t)$ = ENSEMBLE AVERAGE OF FUNCTION VALUE AT TIME t AFTER A REPETITIVE TRIGGERING EVENT

$$\mathcal{F}\{x^E(t)\} = F^E(m\Delta f)$$

Figure 2. Two types of signal analysis available on hard-wired digital equipment.

over an appropriately large ensemble will give the cross spectrum of the steady-state components.

In the case of narrowband random fan noise related to atmospheric turbulence, the pressure signatures at two different locations in the inlet duct are, of course, related by the modal content of the generated acoustic field. However, since the strength and size of the eddies and the location at which they strike the fan plane are random, the modal content of the field is random. Thus, the magnitudes and relative phases of the resulting pressures at any two locations in the duct will be random, and will not contribute to $\overline{F}_{12}$. The average cross spectrum can be used to map strengths and phases of the steady-state field relative to some reference position by varying the location at which x_2 is taken, but some independent method is required to measure the absolute amplitude and phase of the reference signal, x_1.

An alternate method of extracting a steady-state signal from a random background is to use the occurrence of a repetitive event associated with the steady-state source as the zero time for members of an ensemble of signal histories. When such an ensemble is averaged, components having a constant phase relationship with the triggering event will dominate, while contributions from signal components with random phasing, although possibly constant amplitude and/or shape, will tend toward zero. Such an average is referred to as an enhanced signal. The absolute magnitude $|F^E|$ and phase ϕ^E (at the triggering time) of the enhanced signal at any frequency $m\Delta f$ is determined by transforming the average. The spectra of two signals, each enhanced with respect to the same (appropriately chosen) triggering event, may be used in obtaining a cross spectrum

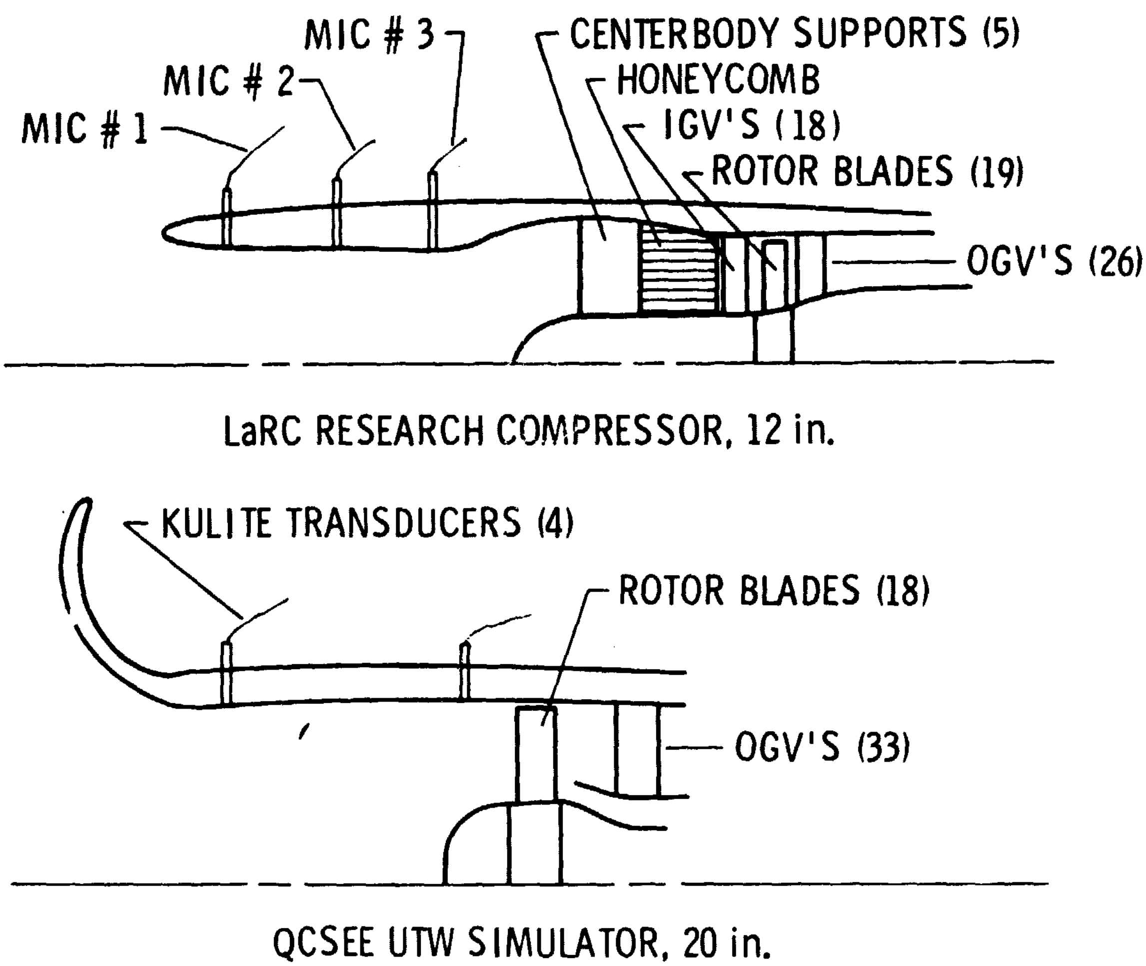


Figure 3. Model turbomachinery inlets employed in testing.

which will equal the averaged cross spectrum for the two signals when the latter is dominated by steady-state phenomena. For the ideal turbomachinery noise source, then, identical information on the structure of the steady-state acoustic field is available from either approach, with the notable exception that absolute magnitudes and phases are obtained via enhancement, while only relative values are available from cross spectra.

EXPERIMENT

The two data analysis techniques discussed above are conceptually simple, but the question still unanswered is whether or not they will yield accurate and repeatable results when applied to signals from flush-mounted or in-duct pressure transducers in the inlet of a turbomachine. Here, data from two different test vehicles are examined. The sketches of the inlets of these machines in figure 3 are not to scale, but are merely meant to indicate the fan configurations and the extent of instrumentation. In each case, the inlet noise radiates into an anechoic environment.

The Langley Research Center's (LRC) 12-inch research compressor was configured during these tests as a single stage transonic machine with a design tip speed of 1301 fps. There were 19 rotor blades, 18 IGVs and 26 OGVs Between five equally spaced centerbody support struts and the IGVs a five inch length of 1/4-inch cell honeycomb was installed. This setup differs considerably from the single rotor, non-IGV situation found in most modern high bypass ratio engines. The struts and IGVs increase the number and strengths of steady-flow distortions on the rotor face, and the honeycomb reduces the scale of turbulence incident on the blades. Thus, the steady-state portion of the acoustic disturbance should be more pronounced here than in any similar test without these devices, and any analysis technique which proves useless here will definitely not yield good results in the engine environment.

The second setup shown is the Quiet Clean Short-Haul Experimental Engine (QCSEE) under-the-wing (UTW) simulator tested by the General Electric Company at their Schenectady research facility. The 20-inch diameter rotor has 18 blades and a hub-to-tip ratio of 0.45. At the design speed, the average throat Mach number is 0.6, the fan tip speed is 1005 fps and the bypass ratio is approximately 12. There are 33 OGVs.

In order to perform signal enhancement, an appropriate trigger signal must be obtained. Ideally, a pulse recurring at the BPF should work, since the rotor blades are designed and constructed to be equally spaced and identical. Nonetheless, there may be slight differences from blade to blade, so that it seems more appropriate to use a once per shaft revolution pulse as the enhancement trigger. Such a signal was available from the LRC compressor, but not from the QCSEE UTW simulator as configured. Therefore, a comparison of methods is possible with data from the former, but not the latter.

As illustrated in figure 3, signals were obtained from three flush mounted microphones in the cylindrical inlet of the LRC compressor. They were at the same azimuth at distances of 40.3, 32.2, and 26.4 inches from the fan face. The microphone signals and the once-per- revolution pulse were recorded on multi-channel magnetic tape for vehicle runs at nominal speeds of 44, 69, and 89 percent of the design speed. Only the last of these represents a supersonic tip speed. More than twelve minutes of continuous data was recorded at each of the speeds which correspond to approximate blade frequencies of 3520 Hz, 5400 Hz and 7020 Hz, respectively.

When the controls of the LRC compressor were set at any fixed position, the speed of the rotor was not constant, but drifted about its mean value in a random fashion. The maximum drift was about $\pm$ 0.5%. The compressor might maintain a fairly constant speed for an extended time, one or two minutes, and then abruptly shift to another speed, or it might drift slowly. This phenomenon, which is apparently due to frequency variations in the electrical power supply, may account, to some extent, for observed nonstationarity of the enhanced signals and the average cross spectra.

A typical example of the drift in the blade passage frequency component in the enhanced signal spectrum is given in figure 4. Here, the changes in BFP (3520 Hz) phases and magnitudes of the spectra of the enhanced signals are plotted versus time for each of the inlet microphones. Each data point corresponds to the average of 2^{10} samples, taken over a period of about 17 seconds. The spectra have a resolution of 220 Hz. The levels are all plotted relative to that for microphone 1 at one minute, and the phase change for each signal is plotted relative to its own value at one minute. Notice that the phase drift shows the same trend at each position, but is somewhat more exaggerated at microphone 1. The levels at microphones 2 and 3 each drifts over a range of about 3 dB, but the difference between the two varies by less than 1.5 dB. On the other hand, the level of the first signal varies by a little more than 2 dB, but shows a different trend than the other two, resulting in changes relative to the others of close to 5 dB.

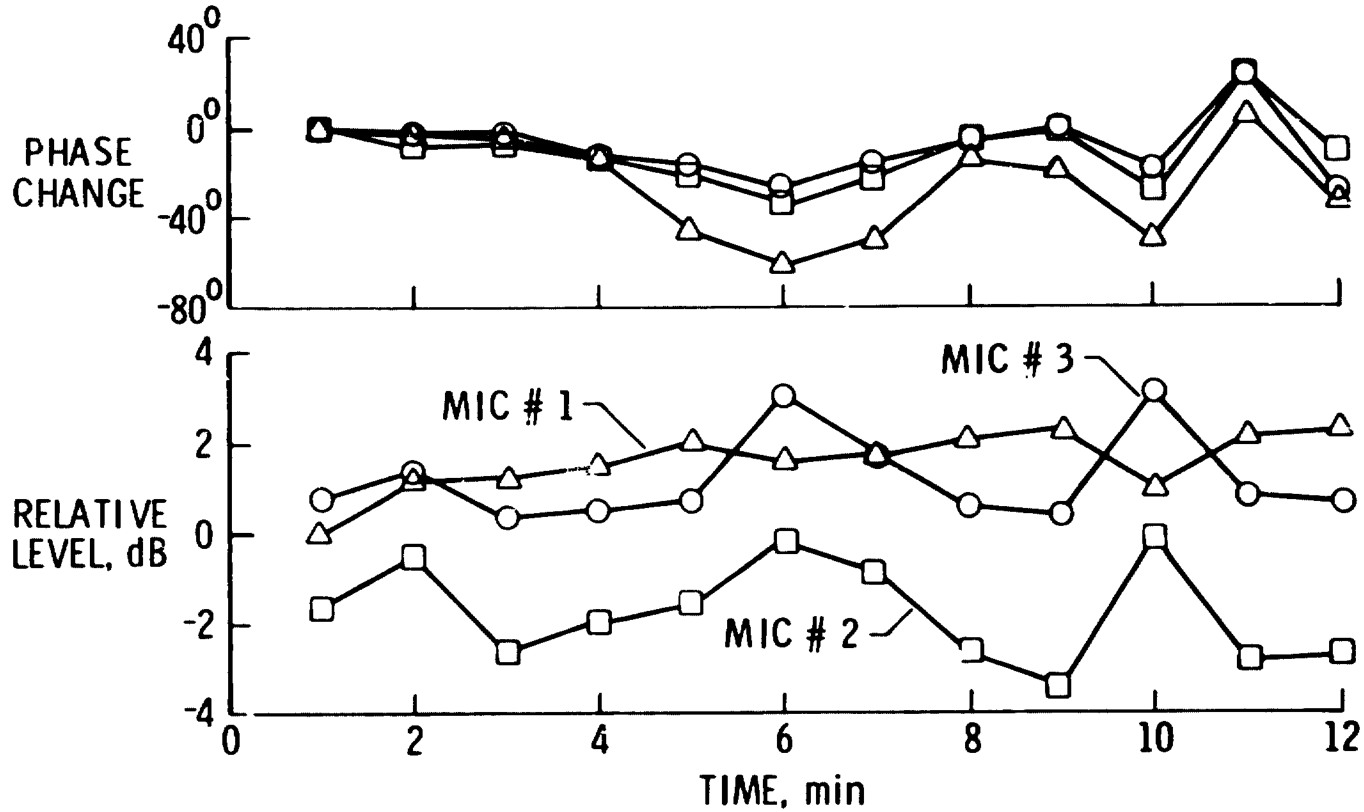


Figure 4. Blade passage frequency (3520 Hz) component of the spectra (220 Hz frequency resolution) of the enhanced signals from 3 flush mounted microphones in the inlet of the LaRC research compressor (fig. 3).

Average cross spectra for the same test run were determined, and a comparison of these with the corresponding cross spectra of the enhanced signals is given in figure 5. An ensemble of 2^8 cross spectra taken over a period of about 19 seconds was averaged to get each value plotted. As noted previously, 2^{10} samples were averaged to get each enhanced signal. This factor of four increase was necessitated in order for both averaging processes to be performed over approximately the same time interval by the available FFT analyzer. Clearly figure 5 indicates that agreement between techniques at any given time is much better than the agreement of either method with itself at a different time. The phase comparison shown is typical of that obtained at all speeds. The level comparison shown is typical in that the data points lie within 1/2 dB of the 45^0 line (except for two "bad" points); however, for all of the higher speeds, the average cross spectrum is larger than the cross spectrum of the enhanced signals by 1/2 to 1 dB on the average during a 12 minute run, thus offsetting the 45^0 regression line from the origin. This is demonstrated in figure 6.

Spectral and signal averaging are compared in figure 6 for three different rotor speeds, corresponding to BPF's of 3520 Hz, 5400 Hz, and 7020 Hz. For the two signals considered here, those from microphones 1 and 2, the agreement of phase information obtained by the two methods is reasonably good, with the least difference observed at the intermediate speed. Amplitude measurements are almost identical at the lowest speed, but disagreement increases with speed. At a BPF of 7020 Hz, the level of the average cross spectrum consistently exceeds that of the cross spectrum of the enhanced signals by about 1 dB. This might indicate significant excitation of lower order modes by the random

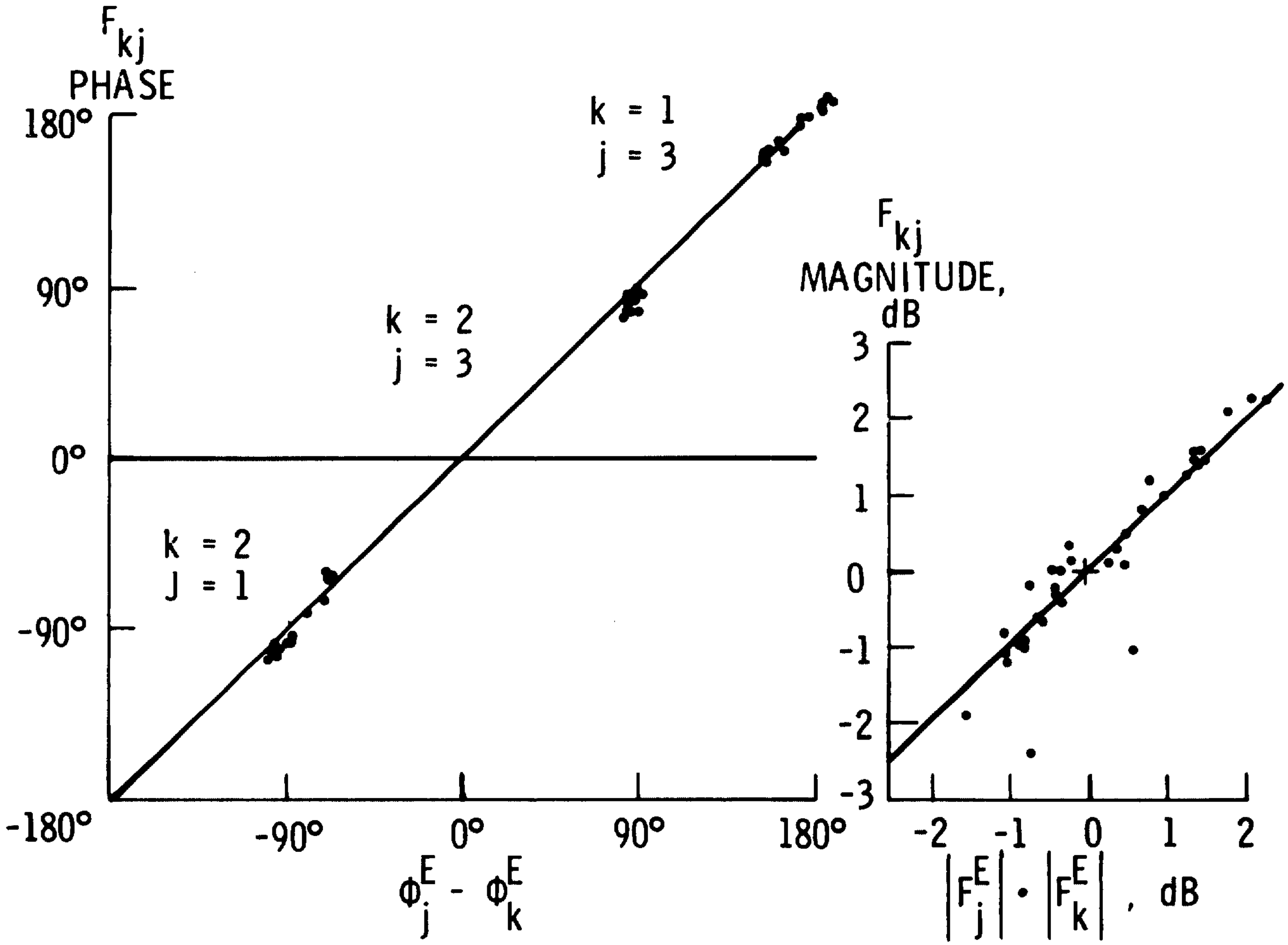


Figure 5. Phase and magnitude comparison of the average cross spectrum and the cross spectrum of the corresponding enhanced signals at a BPF of 3520 Hz. Each point is a comparison of calculations over a time interval of about 20 sec. during a continuous 12 min. test run.

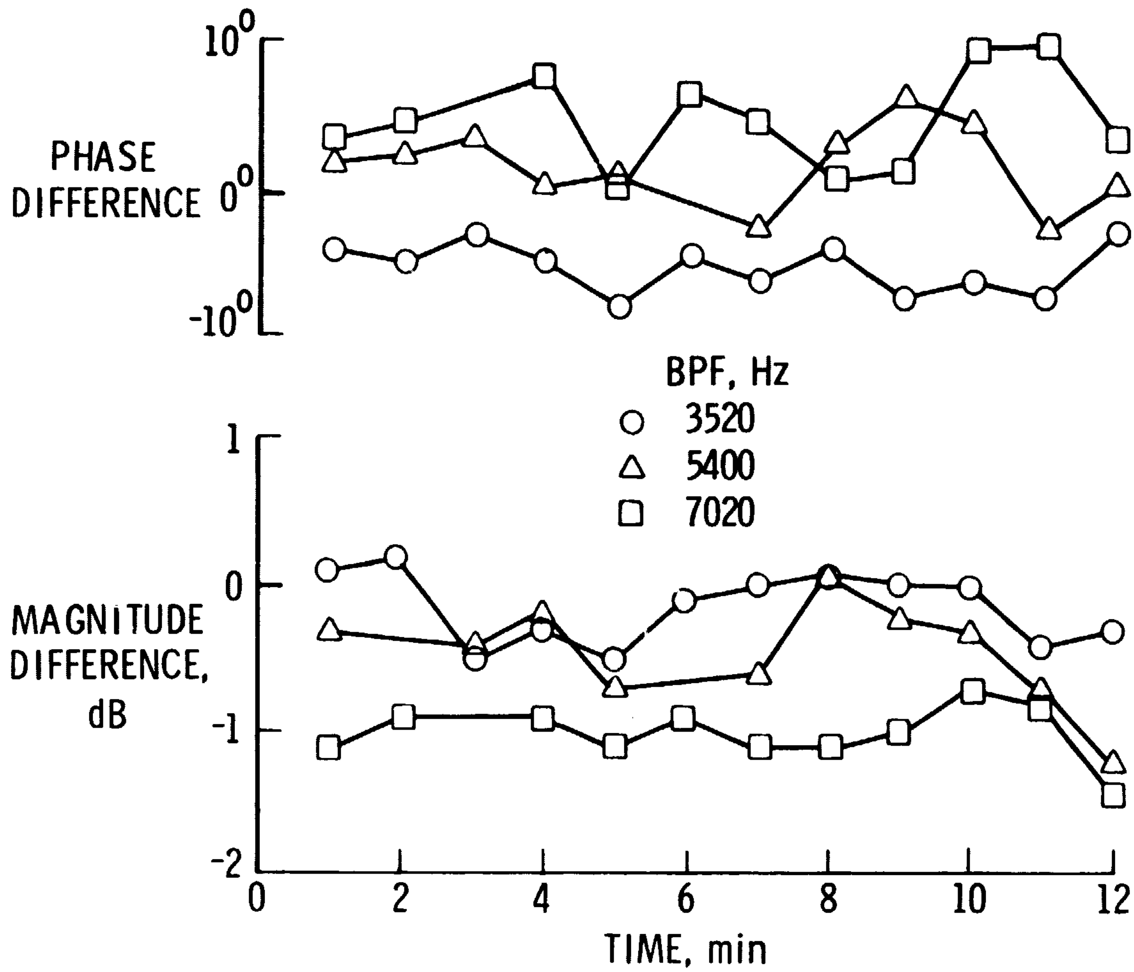


Figure 6. Phase and magnitude of the BPF components of the cross spectra of the enhanced signals from microphones 1 and 2 relative to the corresponding values of the average cross spectra for three different compressor speeds.

ingestion of turbulent eddies, since at higher frequencies these modes are well cut-on nd their axial phase velocities are all close to the speed of sound (minus the flow speed). Therefore, even though the sound field (and the corresponding modal distribution) is random, the standard deviation of the phase difference at two different wall positions at the same azimuth is small, and a contribution from such a source will be present in the average cross spectrum. On the other hand, because the phase with respect to the shaft position of the acoustic pressure at any point due to the random ingestion of large or small eddies is completely random, no contribution from this source is made to the enhanced pressure signals. Hence, the difference in the amplitudes of the average cross spectrum and the cross spectrum of the enhanced signals at the BPF may be a measure of the narrow band random sound which is propagating in well cut-on modes.

In order to obtain the results presented in figures 4, 5, and 6 it is necessary to employ judiciously chosen analysis parameters. That is, the frequency range on the analyzer must be chosen so that one of the frequency bands is fairly well centered on the nominal BPF and wide enough so that the BPF will not wander out of that band as the shaft speed drifts. At the same time, the band must not be so wide that the broadband noise will contribute significantly to the band level. This latter consideration is especially important in averaging cross spectra, since the broadband noise in this case is about 10 dB higher than when the signals are enhanced (for data in the present study). Figure 7 shows how the average cross spectrum amplitude and phase vary during an eight minute test tun, and how using a slightly wider resolution Δf results in much less variation in amplitude. This data is from

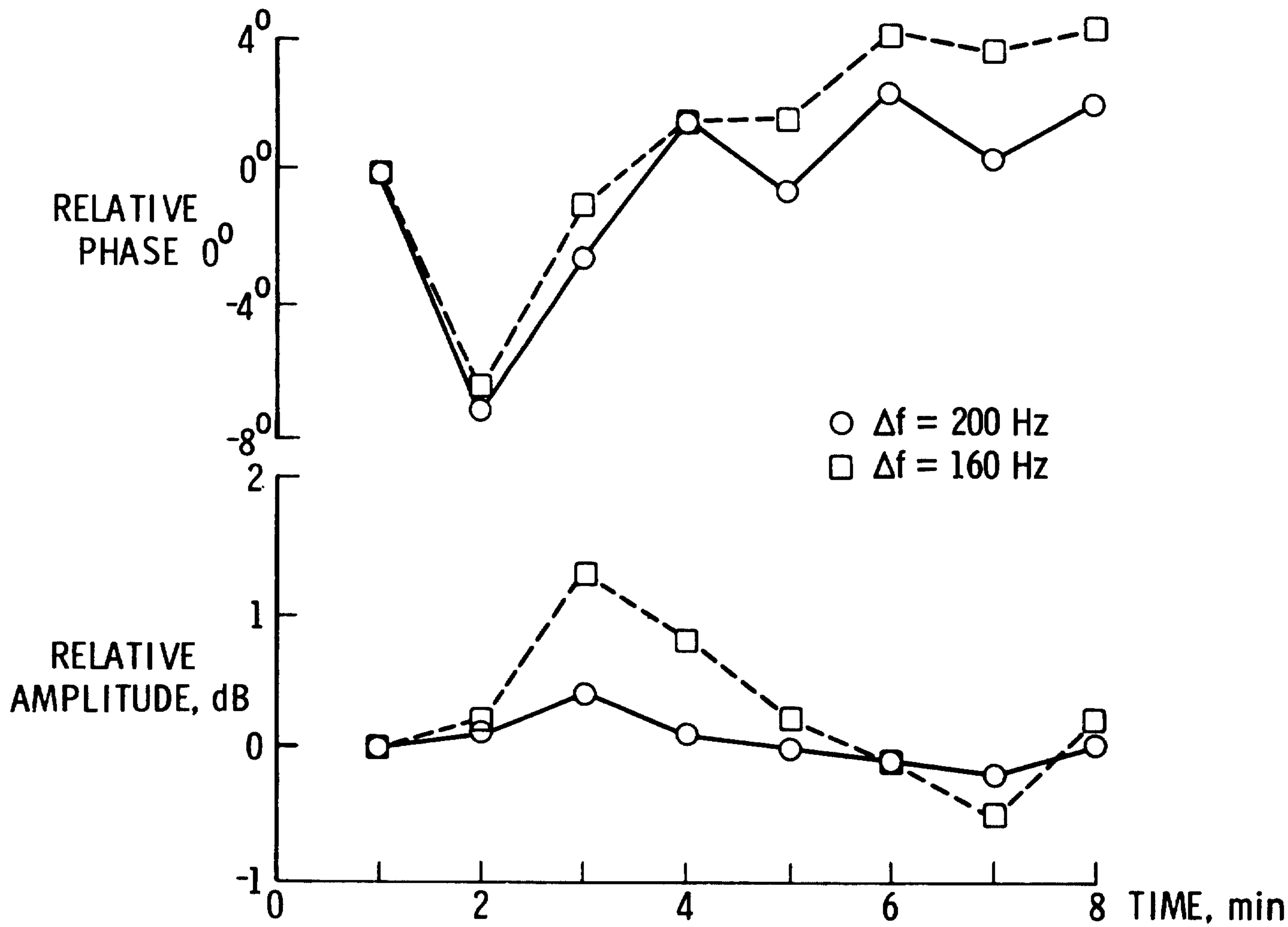


Figure 7. Comparison of variation of the BPF (3200 Hz) component of the average cross spectrum over an 8 minute run of the QCSEE UTW simulator for analysis resolutions Δf of 160 Hz and 200 Hz.

the two Kulite pressure probes located near the fan in the QCSEE UTW simulator. In this instance, the peak is far enough above the broadband noise that contamination from this source is not significant.

CONCLUSIONS

From the limited testing and data analysis performed in this study, some tentative conclusions concerning analysis techniques for the mapping of steady state sound fields in turbomachinery ducts may be drawn. In addition to the obvious advantange that the analysis of an enhanced signal yields absolute magnitude and phase relative to the shaft position, this approach also minimizes the possibility that measurements of the steady state sound will be contaminated by spatially coherent narrowband, random noise such as might be generated by the interaction of the rotor with large scale inflow turbulence. Also, a slowly drifting signal phase is easily detected by signal enhancement, but is easily missed by cross spectral analysis when the phases of the two signals drift together, which is the case when the phase drift is caused by frequency drift.

It appears that the pseudo-steady-state acoustic field which is measured during a 20 second sample may drift slowly with time. This is clearly a real drift and not just statistical scatter of a stationary process, because disagreement between the results of different techniques for nominally the same time interval is much less than the drift of the results of either. This is true even though the time intervels are not precisely the same and four times as much of the data in the interval is analyzed by one technique than by the other. Thus, any non-simultaneous mapping of the acoustical field may result in a pressure amplitude and phase distribution which is not representative of any realized condition.

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