OBSERVED ACOUSTIC AND AEROELASTIC SPECTRAL RESPONSES OF A MOD-2 TURBINE BLADE TO TURBULENCE EXCITATION

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ABSTRACT

Early results from a recent experiment designed to directly evaluate the aeroacoustic/elastic spectral responses of a MOD-2 turbine blade to turbulence-induced unsteady blade loads are discussed. The experimental procedure consisted of flying a hot-film anemometer from a tethered balloon in the turbine inflow and simultaneously measuring the fluctuating airload and aeroelastic response at two blade span stations (65% and 87% spans) using surface-mounted, subminiature pressure transducers and standard strain gage instrumentation. The radiated acoustic pressure field was measured with a triad of very-low-frequency microphones placed at ground level, 1.5 rotor diameters upwind of the disk. Initial transfer function estimates for acoustic radiation, blade normal forces, flapwise acceleration/displacement, and chord/flapwise moments are presented.

INTRODUCTION

Results from a 1982 experiment that examined the acoustic emission characteristics of a MOD-2 turbine concluded that knowing the acoustic and aeroelastic spectral responses of turbine rotor blades to inflow turbulence would be very important to our understanding of the physical processes surrounding the generation of acoustic noise by large horizontal-axis wind turbines. Because unsteady blade airloads are responsible for much of the turbine rotor aeroelastic response and are the source of the aerodynamic component of the radiated acoustic pressure field, as indicated in Figure 1, understanding the former may allow us to estimate in situ unsteady aerodynamic, aeroelastic responses of minimally instrumented turbines from properly executed and processed acoustic measurements. Hemphill [1], for example, showed that distinct acoustic source regions could be identified within the rotor disk of an operating MOD-2 turbine by phase-processing signals from a triad of microphones installed at ground level, upwind of the machine. Kelley et al. [2] found that substantial and sometimes violent dynamic aeroelastic responses (with accompanying high levels of acoustic radiation) can occur with symmetrically shaped airfoil sections operated at incidence angles just below static stall and immersed in a turbulent flow dominated by perturbation space-scales near the chord dimension.

The experiment was therefore designed to directly measure the aerodynamic, acoustic, and elastic responses of a MOD-2 rotor blade in order to (1) help develop a physical understanding of the acoustic generation process; (2) help identify unsteady airload magnitudes on minimally instrumented wind turbines; (3) help identify unknown sources of both low- and high-amplitude and low- and high-cycle fatigue loads; (4) help evaluate dynamic effects that may be associated with vortex generator spoilers installed along the blade's leading edge and the inboard 70% of the span; and (5) help establish the role of the spectral content of atmospheric turbulence in the earth's boundary layer in acoustic noise production and turbine lifetime. This paper discusses a few of the early results of this experiment.

TEST CONFIGURATION

The Boeing MOD-2 Unit No. 2 was the turbine chosen for this experiment. This turbine is one of three MOD-2 machines at the Goodnoe Hills Wind Test Site near Goldendale, Washington, jointly operated by the NASA Lewis Research Center and the Bonneville Power Administration (BPA) for the U.S. Department of Energy. The Goodnoe Hills Site is well-equipped to perform such an experiment because a variety of detailed turbine operational and site meteorological information is available and because of the experimental nature of the site.

Turbine No. 2 was operated for this experiment under the standard operational sequence using Boeing's "five-degree control software" procedures. Vortex generators had been installed near the leading edge of the rotor covering the inboard 70% of each blade span. Groups of six subminiature pressure tranducers were mounted to the upper and lower blade surfaces of Blade No. 1 at two span stations (65% and 87%, or Stations 1164 and 1526, respectively) and chordwise distances of 15%, 40%, and 85%. Station 1164 is located on the outer portion of the fixed section of blade while Station 1562 is located on the movable control tip slightly less than 8 m outboard of the gap between the fixed and movable sections. An accelerometer, with its sensitive axis parallel to the flapwise or out-of-plane direction, was mounted near the inboard surface pressure transducers at Blade Station 1209 (67% span). Standard measurements of strain-gage-derived chord and flapwise moments were made at the locations of the pressure transducers and transmitted via the turbine data system to SERI and NASA multichannel recording facilities along with the remainder of available operational data. The turbine engineering data system limited the data bandwidth of the turbine-related parameters to 35.2 Hz.

Windfield/Turbulence Instrumentation

A commercially-available tethered balloon system, modified by SERI to carry a hot-film anemometer and its associated electronics and a radio-telemetry transmitter, was flown in the turbine inflow to acquire the mean and turbulence spectral characteristics. When the balloon was operated in a profiling mode, the details of the inflow vertical structure could also be examined. The tethered balloon system also carried a small package that sensed and radio-telemetered height (pressure), temperature, windspeed, and wind direction once every 10 s to a ground station located in the SERI Instrumentation Van. There, the data were recorded on two tape systems and presented in digital form in support of the experimental operations. The hot-film turbulence measuring system consisted of a

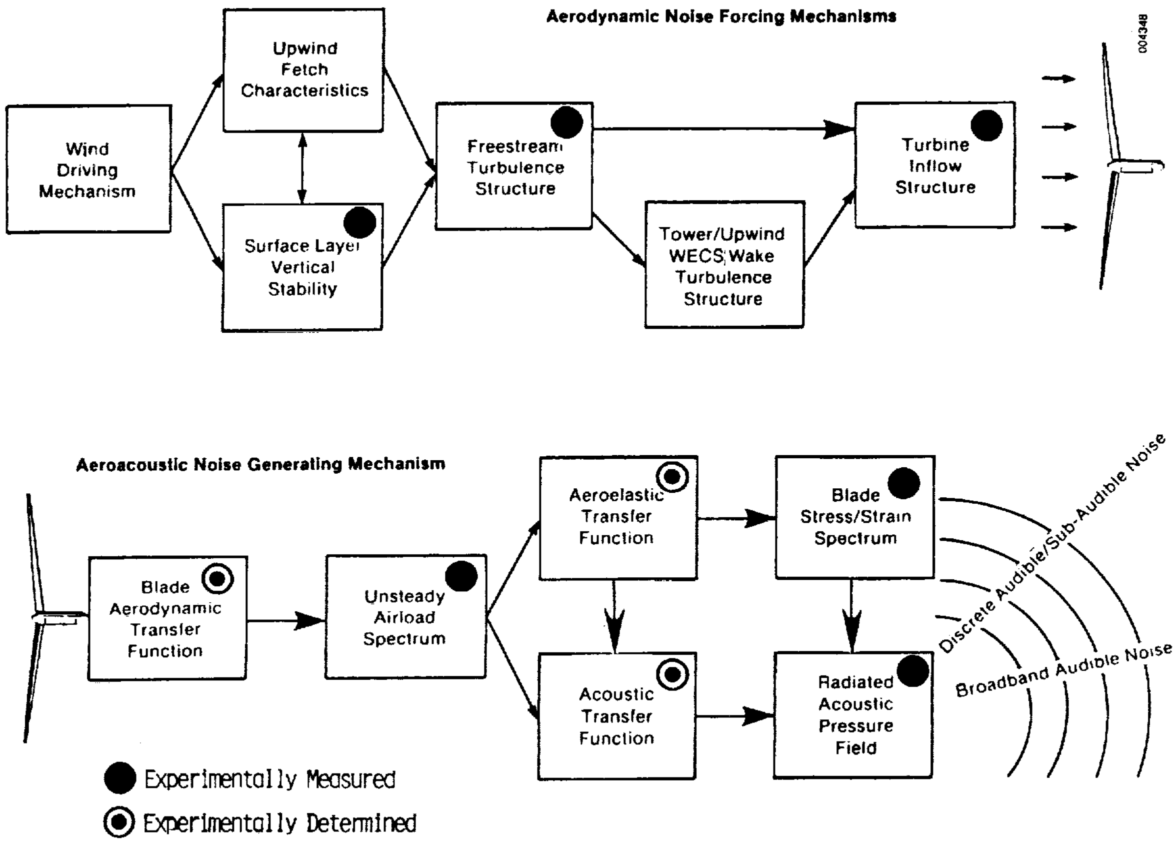

Figure 1. Physical processes responsible for aeroacoustic and aeroelastic blade responses.

0.15-mm-diameter sensor oriented to measure the vector sum of the local horizontal and vertical wind components, the associated bridge network, and a 50-mW digital radio-telemetry transmitter. The receiver, located in the SERI Van, converted the signal from digital to analog form for final processing by a 4th-order polynomial linearizer and time-parallel recording, with selected turbine and acoustic parameters on the same multichannel magnetic tape media. The dynamic range of the hot-film anemometer telemetry link is better than 70 dB and its data bandwidth is 125 Hz, but the final recording was limited to about 48 dB and 100 Hz.

Acoustic Instrumentation

Three very low-frequency (VLF) microphone systems were installed in a right-angle array pattern at ground level upwind of the turbine. The closest microphone to the rotor plane was placed 122 m upwind of the rotor axis. The two remaining microphones were located 15 m farther upstream (1.5 rotor diameters from the disk) and 15 m from each other along a line parallel to the turbine rotor plane. The low-frequency cutoff of the VLF systems was set at 0.1 Hz, and the upper response limit set by the final FM tape recording at 1250 Hz and available dynamic range.

TEST PROCEDURE

The general procedure followed during this experiment was to choose test conditions based on (1) a windspeed range (low range, turbine cut-in to 12 ms^{-1} and high, above 12 ms^{-1}); (2) a wind direction of 270 ±15°; and (3) rotor disk layer hydrodynamic stability as expressed by the gradient or bulk Richardson Number parameter. The tethered balloon system was flown in two modes. Vertical profiles of the rotor disk layer were made before and after each 30-min data run; i.e., heights ranging from about 15 to 108 m. During the actual data runs, the balloon was positioned near hub-height to provide a continuous record of the inflow turbulence for time-parallel recording with the blade surface pressures and acoustic data from which the blade responses could be calculated.

DATA REDUCTION PROCEDURES

The data reduction procedures included (1) data channel response evaluation and subsequent equalization; (2) sampling and Fourier transformation to rms spectral estimates; and (3) computation of turbulence response function estimates.

Data Channel Response/Equalization

The actual transfer function of the turbine engineering data system channels was experimentally measured. Figure 2 plots the modulus (magnitude) of the measured response. As shown, the half-power (-3 dB) point is 35.2 Hz. From our wind tunnel experimentation and previous MOD-2 acoustic measurements, we had good reason to believe there would be considerable response above this figure. We also knew the pressure transducers and strain gage instrumentation were capable of much wider response, because the available bandwidth was wholly limited by the low-pass filter in the telemetry system signal conditioning cards. From our actual measurements of the data channel response characteristics, and knowing the dynamic range of the

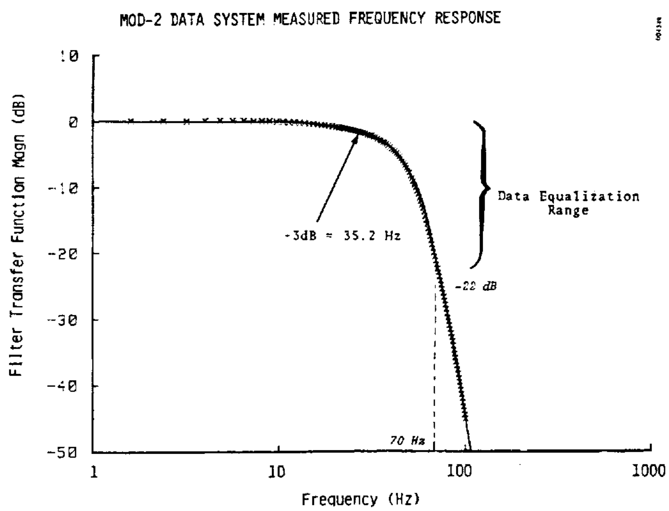

Figure 2. MOD-2 engineering data system channel amplitude response function.

FM recording processes used, we devised an equalization filter which was applied in the frequency domain after Fourier transformation. This equalization process is essentially the inverse of the response shown in Figure 2 with the maximum frequency at which it is applied at 70 Hz. This upper frequency limit was arrived at by conservatively estimating the dynamic range of the FM recording processes used by SERI and NASA at about 40 dB maximum. (We believe, for example, the actual SERI figure was between 43 and 48 dB.) At 70 Hz the data system analog filter response was -22 dB, which would allow for sufficient equalization and not exceed the assumed 40-dB dynamic range of the FM recordings. Thus, a maximum gain of 22 dB at 70 Hz is applied to the recorded data in the equalization process.

Sampling and Fourier Transformation

The results in this paper are derived from a data run recorded on the evening of 16 August 1983 between 2230 and 2300 hours local standard time. Because of the nonstationary characteristics of the atmospheric input, each 30-min data run has been divided into six 5-min segments. The final 5-min segment of this particular series was chosen for detailed response analysis reported on here because (1) a minimal vertical variation was found in the height of the hot-film anemometer with respect to the rotor disk (a standard deviation of 6 m, compared with other 5-min segments in which variations of more than ±15 m were found); and (2) relatively substantial turbulent energy levels were found in the high-frequency range. Table 1 summarizes pertinent turbine operational and inflow turbulence values for this 5-min segment.

We chose a vertical window of ±10 m from the mean hot-film anemometer height as the region from which we would extract blade dynamic data needed to calculate response estimates. This choice resulted in the definitions of the two segments of the rotor disk pictured in Figure 3. Previous experience indicated that subtle changes occur in the blade response as it ascends and descends (driven by gravity, most likely) and that therefore we should examine the response of the blade as it passed through the measured layer in both directions. By delaying data conversion and

Table 1. Summary of Important Turbulence Excitation and Turbine Operation Flow Angles for Analyzed Data Segment

Turbulent Layer Structure Parameters	
Mean measurement height (above tower base)	78 ± 6 m
Mean horizontal wind speed	7.39 ms^{-1}
Turbulence intensity	8.0%
Turbulence integral scale ℓ	2.89 m[a]
Turbine Blade Operating Angles	
Indicated mean blade angle (ref. at Sta. 1260)	+0.62°
Calculated mean angle of attack (Sta. 1164)	11.6°
Calculated mean angle of attack (Sta. 1562)	9.6°

[a]1.3 chords referenced at 80% span.

Fourier transformation a fixed amount from the time the blade was at the bottom of its travel (parallel to the tower base), we could start the 0.5-second conversion period to coincide with the windows shown in Figure 3. While some differences were noted, the data presented in this paper are based on the averages of responses found in the ascending and descending sampling windows. Inflow turbulence data were collected using the same sampling scheme and delayed to allow propagation at the 7.4 ms^{-1} mean windspeed to reach the disk (employing the frozen turbulence hypothesis). Similarly, acoustic data were calculated from the in-phase portion of the rms cross-spectral estimate from the two microphone systems parallel to the rotor disk and 1.5 diameters upstream. An additional delay of 0.5 seconds was added to account for the propagation time from the affected disk area to the microphones. The 5-min data segment resulted in a total record of 40 seconds containing 80 blade passages through the turbulent excitation layer from which the averaged rms spectral estimates were derived. A total of 81,920 data points were processed. The resulting resolution bandwidth of the transformation is 2 Hz.

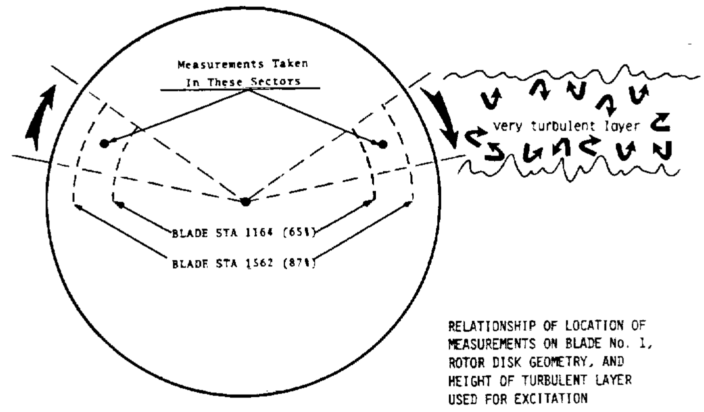

Figure 3. Relationship of measurement locations on Blade No. 1, rotor disk geometry, and height of turbulent layer used for excitation.

Response Estimate Calculations

The response estimates were calculated by taking the ratio of the equalized blade pressure or other turbine parameter rms spectral estimate to the reference turbulence spectrum. Thus, results are referenced in terms of the units of the particular parameter per ms^{-1}.

DESCRIPTION OF TURBULENCE EXCITATION

Figure 4 plots the detailed vertical windspeed profile measured immediately at the conclusion of the 5-min data segment. The minimum vertical resolution of this profile has been limited to 6 m. The turbulent excitation layer is characterized by the scatter in the data points. Figure 5 presents the averaged, normalized power spectral density of the turbulence in this layer which also served as the reference from which response estimates have been calculated. The relatively significant high-frequency (short wavelength) energy content is apparent even in this averaged spectrum. The location of the correlated turbulent eddy region, defined by frequencies higher than the integral scale ℓ, is shown at right. Some differences in the spectral characteristics above this frequency may be noted.

TEST RESULTS

Representative examples of response estimates have been divided into three groups: acoustic, aerodynamic, and aeroelastic. While it would be interesting and perhaps significant in some cases, we have not attempted to combine these categories in this paper.

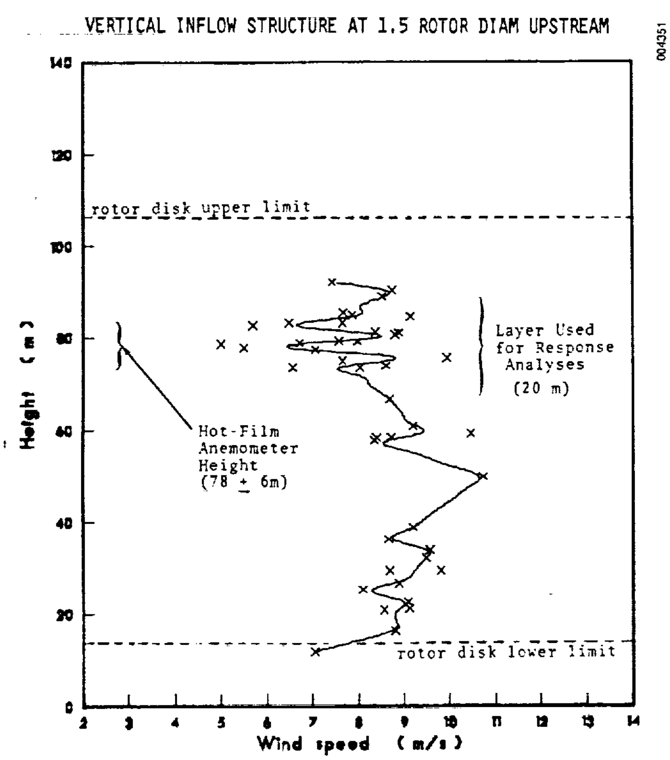

Figure 4. Details of vertical inflow structure measured 1.5 rotor diameters upstream of MOD-2 disk.

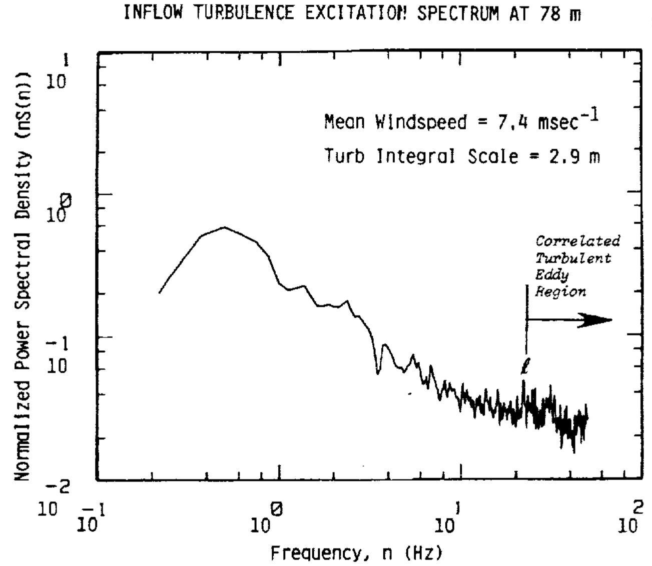

Figure 5. Averaged normalized power spectral density of turbulent excitation layer at 78 m.

Low-Frequency Acoustic Response Estimates

Figure 6 plots the low-frequency acoustic radiation response in Pa/ms^{-1} over a range of 2 to 100 Hz (the acoustic data were not limited by the turbine engineering data system low-pass filters and so can be presented to 100 Hz). The abscissa has also been calibrated in terms of the reduced frequency parameter k (shown in italics) as referenced to the chord dimensions and relative blade speed at 80% span. The k parameter is defined by $k = \pi cf/U$, where c is the chord dimension; f, the cyclic frequency; and U, the relative blade speed.

Blade Aerodynamic Response Estimates

Two examples of the blade aerodynamic response are given in Figures 7 and 8. Figure 7 plots the normal force response in units of kPa/ms^{-1} as measured at the 40% chord position at both the inboard (65% span or Blade Station 1164) and outboard (87% span or Blade Station 1562) span locations. Figure 8 indicates the differences in response seen at the 15% and 40% chord positions at the outer span station (1562).

Blade Aeroelastic Response Estimates

Figures 9, 10, 11, and 12 are a representative look at the aeroelastic response of the blade. Figures 9 and 10 plot the chord and flapwise moment responses in $N\text{-}m/ms^{-1}$ at the inboard (Station 1164) and outboard (Station 1562) span locations. Figures 11 and 12 present the flapwise acceleration and displacement responses in ms^{-2}/ms^{-1} and m/ms^{-1}, respectively, at Blade Station 1209 on the fixed-pitched portion of the blade.

RESPONSE IN TERMS OF TURBULENCE SPACE SCALE

Previous SERI wind tunnel experiments with symmetrically shaped airfoil sections [2] showed that strong and occasionally violent buffet-type responses could develop at incidence angles approaching but remaining below static stall. In terms of the reduced frequency parameter k, the buffet onset was generally found to be near $k = 0.5$ and extended to at least $k \cong \pi$. The

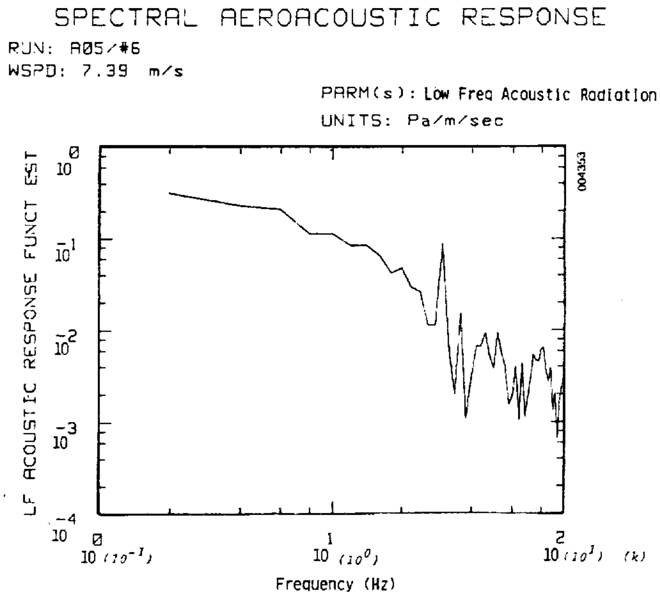

Figure 6. Measured low-frequency acoustic radiation response function.

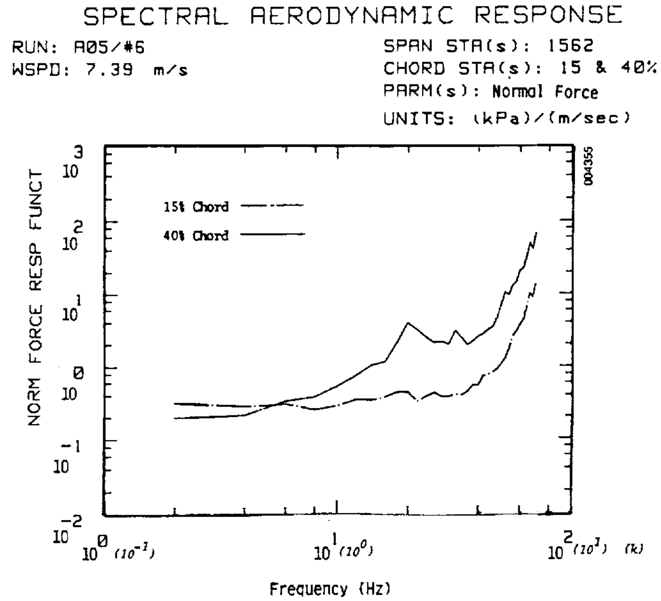

Figure 8. Measured normal pressure force response functions at Blade Station 1562 (87%) at 15% and 40% chord stations.

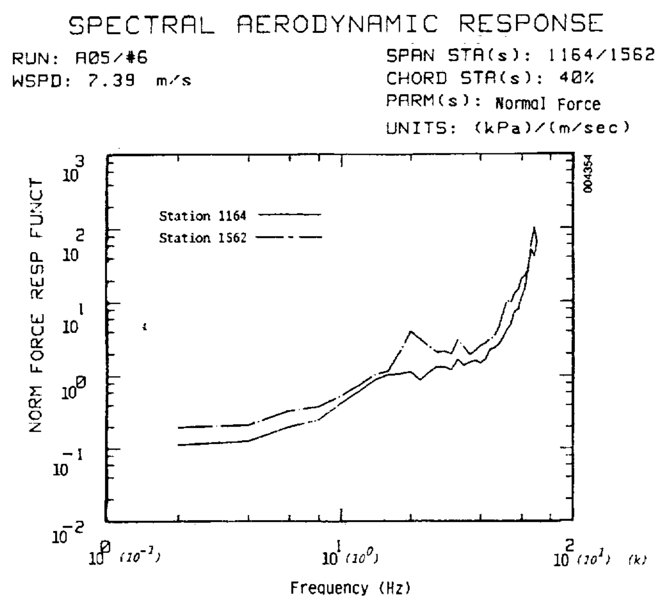

Figure 7. Measured normal pressure force response functions at 40% chord and Blade Stations 1164 (65%) and 1562 (87%) span.

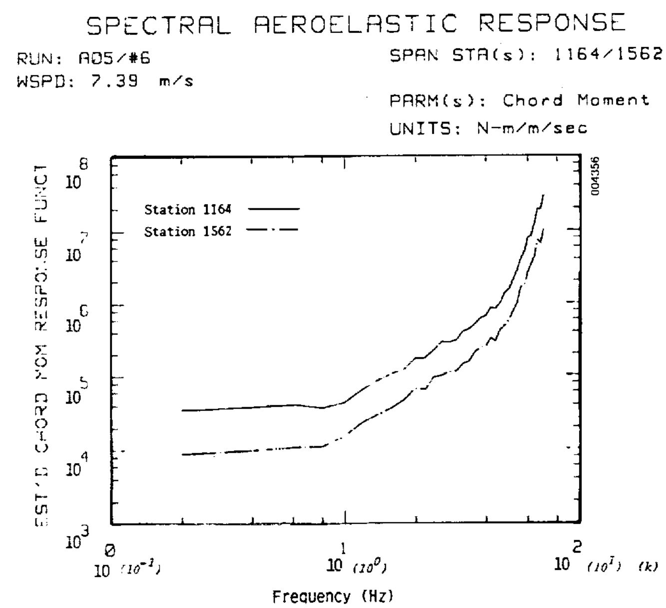

Figure 9. Measured blade chord moment response functions at Blade Stations 1164 and 1562.

response shown on most of the previous figures seems to extend higher than that figure. However, these tests agreed with the wind tunnel results in that the buffet response also increases as the flow perturbations or turbulent eddy size approaches the dimensions of the section chord. Figures 13, 14, and 15 have been replotted using the acoustic, 40%-chord normal force and chord moment response data of Figures 6, 7, and 9 of the turbulent eddy size or perturbation wavelength normalized by the chord dimension at 80% span. The wavelengths defined by the integral turbulent length scale ℓ are also shown. As previously mentioned, the turbulent integral scale roughly refers to the largest correlated eddy size or, in other words, the upper limit on correlated turbulence space scales.

CONCLUDING REMARKS

This preliminary assessment of the unsteady response of MOD-2 turbine blade, from one rather well-behaved case, indicates that unsteady blade loads are very sensitive to the spectral content of the turbulence encountered around the swept area of the rotor disk. The greatest sensitivity appears to be to turbulent eddy sizes on the order of the blade chord or less. A

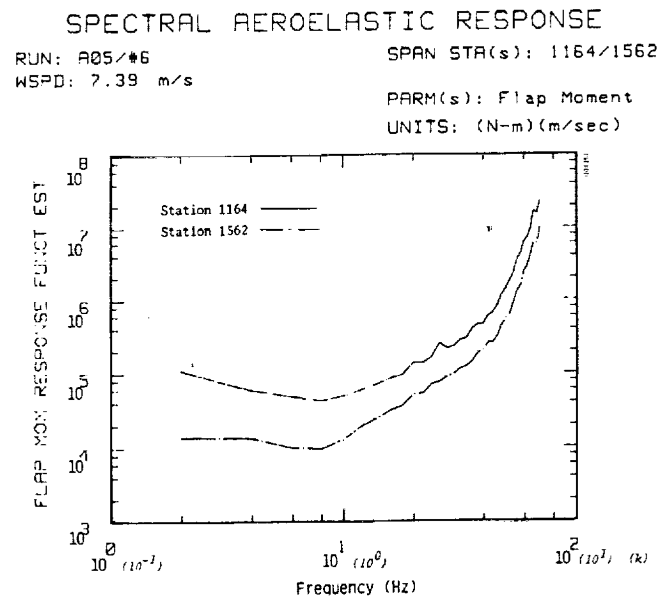

Figure 10. Measured flap moment response functions at Blade Stations 1164 and 1562.

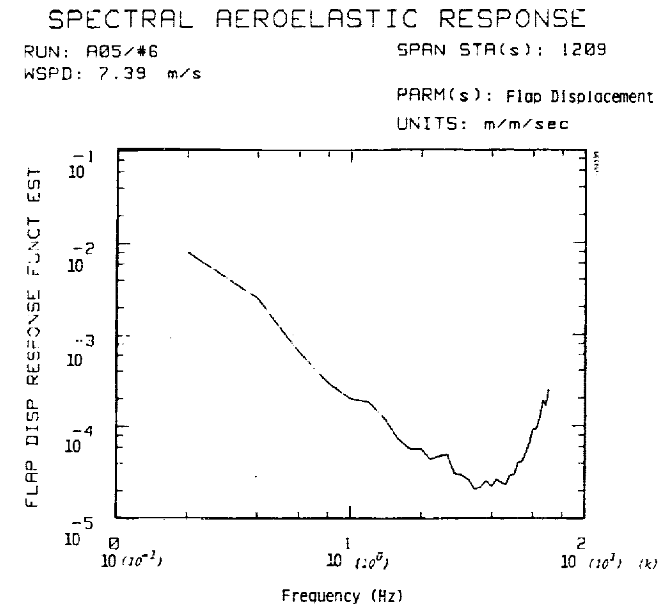

Figure 12. Measured flapwise displacement response function at Blade Station 1209.

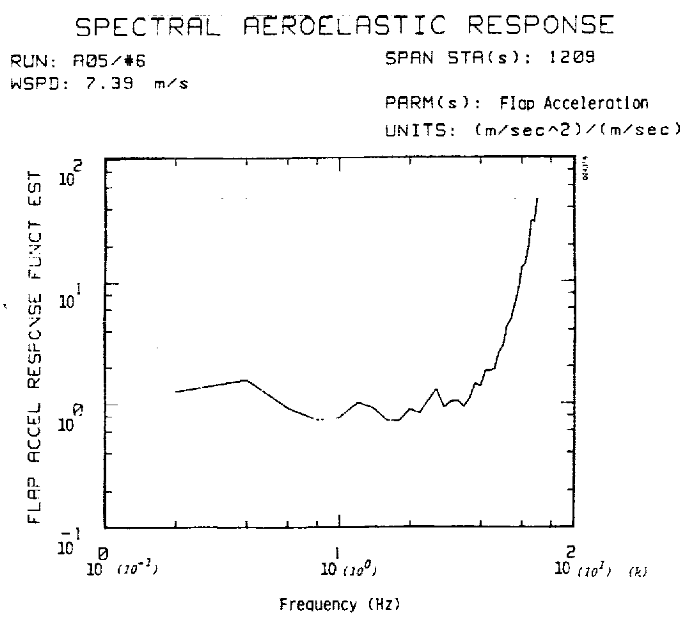

Figure 11. Measured flapwise acceleration response function at Blade Station 1209.

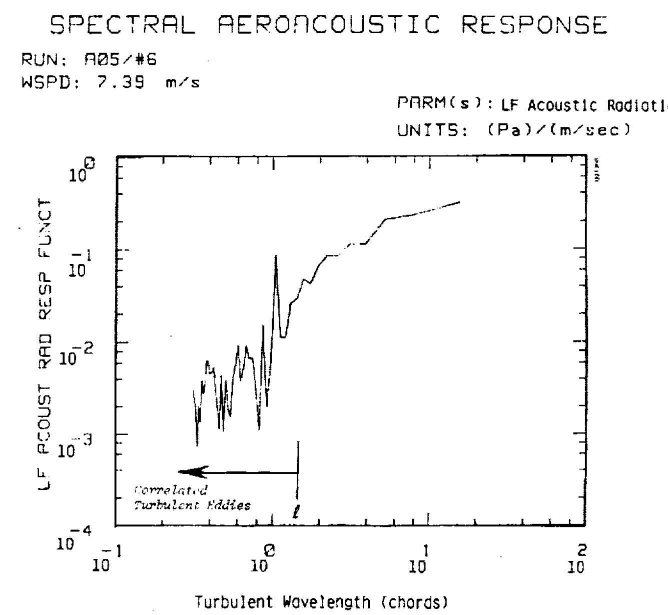

Figure 13. Measured low-frequency acoustic radiation response as a function of turbulence space scale.

correlation also seems to exist between the turbulence integral scale and the resulting unsteady blade response as indicated by the acoustic, aerodynamic, and aeroelastic response estimates.

The outboard blade station (1562) on the movable tip is noticably less sensitive to the turbulence until the turbulence scales become less than the section chord length. One possible explanation for this is that the mean attack or incidence angle of the flow with respect to the outer span station is about 1^{o} less than the inboard station and thus slightly farther away from the static stall condition, a situation that we know from our wind tunnel experience usually indicates a reduced unsteady response. Also, the inboard section was fitted with vortex generators whose function is to delay separation and increase the maximum section lift.

The data-system-imposed maximum bandwidth limitation of an equalized 70 Hz prevents us from determining when the curves begin to fall. However, Figure 6, which contains the acoustic radiation response estimate, seems to indicate that a peak may exist at around 80 Hz, and it hints at one even higher. Additional measurements with wider data bandwidths are needed to confirm the effective upper limits of turbulence sensitivity, but some clues may be gathered

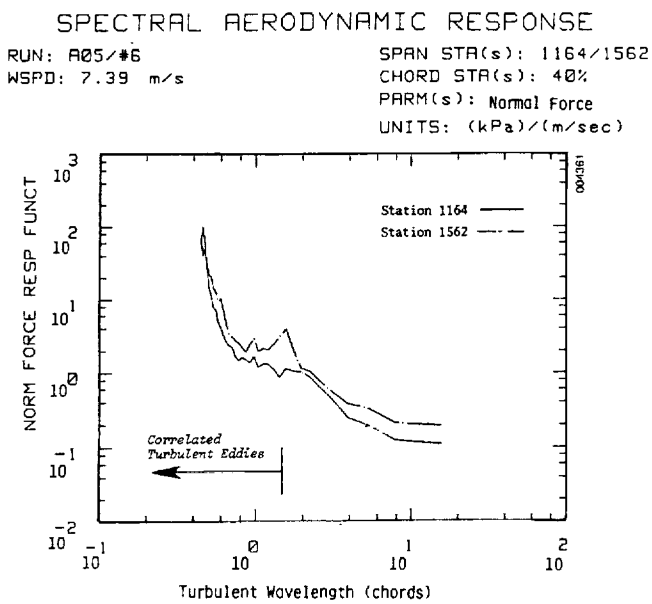

Figure 14. Measured 40%-chord normal force response function at Blade Stations 1164 and 1562 as a function of turbulent space scale.

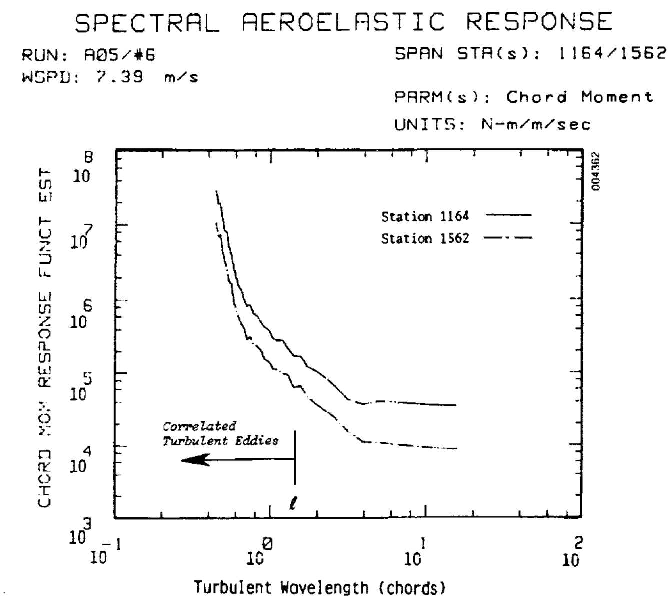

Figure 15. Measured blade chord moment response functions at Blade Stations 1164 and 1562 as a function of turbulent space scale.

from the SERI acoustic data set which has been analyzed statistically up to 160 Hz in 1/3-octave bands.

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