ACOUSTIC NOISE GENERATION BY THE DOE/NASA MOD-1 WIND TURBINE

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ABSTRACT

The results of a series of measurements taken over the past year of the acoustic emissions from the DOE/NASA MOD-1 Wind Turbine has shown the maximum acoustic energy is concentrated in the low frequency range, often below 100 Hz. The temporal as well as the frequency characteristics of the turbine sounds have been shown to be important since the MOD-1 is capable of radiating both coherent and incoherent noise. The coherent sounds are usually impulsive and are manifested in an averaged frequency domain plot as large numbers of discrete energy bands extending from the blade passage frequency to beyond 50 Hz on occasion. It is these impulsive sounds which are identified as the principal source of the annoyance to a dozen families living within 3 km of the turbine. The source of the coherent noise appears to be the rapid, unsteady blade loads encountered as the blade passes through the wake of the tower structure. Annoying levels are occasionally reached a nearby homes due to the interaction of the low-frequency, high energy peaks in the acoustic impulses and the structural modes of the homes as well as by direct radiation outdoors. The peak levels of these impulses can be enhanced or subdued through complex propagation.

INTRODUCTION

Background

During the fall of 1979, as the DOE/NASA MOD-1 Wind Turbine was undergoing a series of engineering shakedown tests, a number of sporadic and totally unexpected noise complaints were received from a few homeowners living within a 3 km radius of the installation atop Howard Knob near Boone, North Carolina. These complaints came as a surprise since a series of earlier sound measurements taken at the 100 kW MOD-0 wind turbine near Sandusky, Ohio indicated acoustic emissions associated with the machine operation were indistinguishable from the wind-dominated background at distances greater than 200 m (ref. 1). These early reports associated with the MOD-1 were very puzzling since complaints were not received each time the turbine was operated and attempts to correlate the type and location of the complaints with machine operating modes proved inconclusive. It was at this point the NASA Wind Energy Project Office and the SERI Wind Energy Branch entered into a cooperative effort to document and establish the source of the annoyance with the ultimate objective being the implementation of a suitable mitagation procedure as soon as practical.

The Nature of the Complaints

It should be pointed out, while the general character of the complaints has not changed materially from the initial reports received, the total number of families known to be affected has not increased above the dozen identified within the first few months, even though more than 1000 families live within the 3 km radius. Thus it is many of the same families being annoyed at various times, some more often than others. Figure 1 shows the location of the complainant homes with respect to the wind turbine and also indicates those locations reporting a higher frequency of annoyance.

Most homeowners describe the annoyance as consisting of periodic "thumping sounds and vibrations" similar to the sensation of having someone walk heavily across a porch or hearing a heavy truck passing with a flat tire. Some have reported the rattle of loose picture frames or small objects and most agree the noise level is greater inside their homes than out. Most complainants site the periodicity of the sounds and vibrations as being the most annoying aspect with the level becoming louder and more consistent during the evening and nighttime hours.

The SERI Program

In cooperation with NASA, the SERI Program has had as its objectives the identification of the physical mechanisms responsible for the generation of the noise, its propagation to the homes below, the resulting subjective responses and development of suggestions for methods to mitagate the annoyance. These resulting mechanisms must adequately explain the following questions regarding the perceived characteristics of these sounds:

1. Why is it the noise does not reach annoying levels each time the turbine is operated?
2. Why are some families annoyed more often than others and why does the situation confine itself to such a tiny fraction of the overall population potential?
3. Why does the noise appear more noticable inside the homes and why does it become more consistent and perhaps louder during the evening and nighttime hours?

The purpose of the SERI effort goes beyond the specific noise situation associated with the MOD-1 and the knowledge gained will be applied to provide definitive noise evaluations and predictions for sound levels and annoyance potentials for a number of generic wind turbine designs.

THE PROCEDURE OF THE INVESTIGATION

As a result of the initial assessment of the situation, it was recognized the problem has three major components; i.e., the actual noise generation process which was suspected to be aeroacoustic in origin, the propagation of low-frequency sound in complex terrain, and the annoyance-generating mechanisms in the affected homes. Efforts were initiated with the MIT Department of Aeronautics and Astronautics for development of analytical techniques for assessing the physics of the sound generation and the Pennsylvania State University for investigating the propgation aspects. The initial results of these activities are being reported separately (refs. 2 and 3).

The need for a definitive set of physical measurements which documented the acoustics characteristics of the sounds, the atmospheric structure present and controlling the propagation, and the structural and ground motions of affected houses was recognized and considerable effort has been mounted towards this end. Further, the scope of these activities has extended beyond the MOD-1 and additional measurements have been performed using the MOD-0 and a small wind turbine installed at the Rocky Flats Test Center near Golden, Colorado in order to obtain important supporting data.

Measurements

Two major field studies have been accomplished during the past year. The first (March 1980) acquired both near- and far-field acoustic and house structural motions data during an actual annoyance episode. In addition, two acoustic sounders and two tethered balloon systems were employed to gain information on the vertical structure of the atmosphere to assess the propagation of the turbine sounds. The locations of this equipment is shown in Figure 1. The second study investigated the acoustic emissions at both 35 and 23 rpm under loaded conditions but only in the acoustic near-field (June 1980).

Data Reduction and Analysis

The supporting turbine operating data; i.e., blade pitch, rotor position, and nacelle yaw angles, generator output, and hub-height wind speed, were digitized and stratified into 2-3 minute records which exhibited relatively stationary statistics. The near-field acoustic data corresponding to these periods were analyzed by both frequency and time domain methods. The former was accomplished using a standard 800-line, narrowband FFT spectrum analyzer. Impulses found in the acoustic signal were analyzed with the spectrum analyzer in the time domain mode and under computer control to process sample estimates of various waveform criteria such as pulse risetime, riserate, total energy content, and peak overpressure. The dual-channel, 400-line mode of the analyzer was used to study the dynamic interactions between the pressure fields and the house structural motions.

RESULTS

Turbine Acoustic Emissions

Analysis of the near-field acoustic signals has shown the emissions can be composed of at least three types of acoustic energy which can exist in different proportions depending on the characteristics of the winds blowing by the turbine. Figure 2 illustrates a sound pressure frequency spectrum in which two of the three posible types of acoustic emissions are represented. This spectrum is composed of mostly broadband, incoherent rotor noise with a few discrete tones out to about 10 Hz and two distinct tones at 60 and 79 Hz whose source are the mechanical and electrical equipment of the turbine. The low frequency discrete tones are the reflection of unsteady loading on the blades as they move around the rotor disk and are brought about by such factors as wind shear and tower shadow induced velocity gradients (refs. 2 and 4). Figure 3 depicts the corresponding pressure-time plot of a portion of the period used to obtain the average of Figure 2. The period represented encompasses two complete rotor revolutions and two passages by the tower for each blade. The wind speed at hub height was 9 m/s (20 mph) and rather steady in character.

The existence of strong, highly coherent impulses imbedded in the normal, broadband rotor noise is illustrated in Figures 4 and 5. Figure 4 displays the pressure-time history plotted over two blade revolutions. Compare the sharpness and the higher peak overpressures of these pulses with Figure 3. Figure 5 plots the corresponding averaged, sound pressure spectrum for this period. Note the many, many discrete tones extending all the way out to 100 Hz! The wind speed during this period was approximately 11 m/s (25 mph) and was more gusty than the wind characteristic for the period of Figures 2 and 3. Figures 6 and 7 increase the time resolution for these same pressure-time plots allowing a comparison of the waveforms in greater detail. The more gentle trace of Figures 3 and 6 was made when the rotor was parallel to the SE flat of the support tower; that of Figures 4 and 7, as the blade passed slightly closer to the tower leg while perpendicular to the tower N-S diagonal. The blade came slightly closer to the tower leg (5 leg diameters) while near the N-S axis as compared with the 7.5 diameters while parallel to the tower flat.

Figure 8 illustrates a pressure-time history similar to Figures 4 and 7 but this impulse was received outside of House #8 which is about 1 km to the ESE and about 300 m lower in elevation than the turbine. The home at this time was experiencing what was described by SERI personnel in the house as "very heavy thumping" and confirmed by the residents, two of which were present. The rotor was slightly oriented closer to the south leg of the tower but almost parallel to the SE flat as in Figures 2 and 3. The wind at the turbine site was 11-13 m/s (25-30 mph) and gusty. Notice this plot shows two major downward-traveling pulses. If one measures the time delay between them (81 msec) and computes the linear distance corresponding to this delay for a tip speed of 111 m/s (35 rpm) is 9.3 m (31 ft). The tower leg separation at this point is 9.5 m (31 ft).

From the preceeding, whatever is producing these large excursions in the acoustic pressure field is taking place in the lee of the 0.5 m diameter tower legs and the source of the low-frequency "thumping" sounds reported by the residents. Coherent pulses of this type are best evaluated using energy techniques which involve analysis in both the time and frequency domains. The time domain is used to establish waveform characteristics of the impulses; i.e., the risetime, riserate, total energy content, and peak overpressure. The frequency domain allows the determination of the frequency distribution of the impulse energy. Figure 9 plots the energy distribution with frequency for the time history shown in Figure 8.

A total of over 75 series of impulses have been processed using the SERI time domain program and the results correlated with turbine operating parameters. The results of this analysis can be summarized as follows:

1. The peak overpressure and riserates are most highly correlated with windspeed, rotational speed (rpm), and the blade-to-tower leg distance.
2. Little or no correlation could be found with generator output (machine loading) since peak overpressures could be found which were as high or higher unloaded.

Figure 10 summarizes the variation of impulse peak overpressure as a function of wind speed. Note the tendency for two groupings of data points about 10 dB (re 20 μPa) apart. Many of the points representating data taken at 35 rpm lie near the upper curve and those at 23 rpm near the lower, but not all!

Propagation

The Penn State work has concluded the following (ref. 3):

1. Due to the extremely low atmospheric attenuation for sound frequencies below 100 Hz, high levels of such noise generated by wind turbines which are "unacceptably" above local ambient may produce unacceptably high noise levels in the far field due to meteorologically dependent atmospheric refraction.
2. The intensity, duration, and location of enhanced (or subdued) far-field noise levels cannot be predicted without very high resolution meteorological data (wind speed and direction, vertical shear, and thermal parameters) and therefore suppression of the noise source appears to be the only, long-term, viable solution.
3. The conditions responsible for optimum power generation at the MOD-1 site are also the ones most likely to produce adverse noise propagation.
4. Airborne propagation controlled by atmospheric refraction is the primary transmission mechanism to the homes below and surface and ground propagation is negligible.

House Acoustics and Vibration

In order to address the manifestation of both low-frequency sounds and vibration, a detailed analyis of recorded acoustic and vibration data taken at two of the residences during the March 1980 tests has been accomplished. These homes include a double-wide, mobile structure (House #7 in Figure 1) and a two-story, frame building (House #8). These particular homes were chosen in view of the high frequency of annoyance reported by the families. Acoustic measurements using special, low-frequency microphones were taken simultaneously inside and closeby outside. Vibration data using seismic-range sensors included both vertical and horizontal floor and single-axis window accelerations. The measurements in each home were located in the room in which the residents had decided the noise was most noticeable. Both homes were equipped with storm windows but the frame house was substantially tighter.

From the description of the complaints, it was suspected the "thumping" sounds heard inside the houses were being re-generated by the interaction of the acoustic impulses from the turbine and the physical structure of the house. It also has been suggested the sounds heard are largely the result of the direct radiation in the 20-50 Hz band. To establish the acoustic absorbtivity as a function of frequency the cross-correlation of the inside and outside sound pressure levels was established using the technique of coherent power (coherent power = coherence x autospectral density of indoor sound pressure signal, ref. 8). Figure 11 shows the major coupling through the walls and support structure of House #7 occurs in the 7-14 and 20-26 Hz bands with a narrow band at 62 Hz. In contrast, House #8 exhibits the maximum direct coupling only in the lower 7-14 Hz band, as indicated in Figure 12.

The structural resonances of the homes were determined by either exciting the structure through a rapid door close or by recording background vibration levels for several hours. Tables 1 and 2 summarize the major normal and cross-coupling resonances in the 0.2 to 100 Hz range. The confirmation that most sounds were being re-generated by the structure under impulsive acoustic loads was accomplished by measureing the time delay between the arrival of the peak impulse at the outside microphone and the initial onset of sound energy peaks in the 10-20 Hz, 31.5, 63, and 125 Hz octave bands measured in the subject room. The physical separation between the outdoor microphone and the indoor was about 23 m with the outdoor closer to the wind turbine. This separation would account for approximately a 73 msec delay between microphones at this altitude and air temperature. The actual delay, which is illustrated in Figure 13 for the 63 Hz octave vibration band, has been determined to be in the range of 120-125 msec or about 40% longer than would be expected from propagation in air alone. Thus much of the acoustic energy impacting the house and not being initially reflected is being stored in the structure as stresses, a portion of which is subsequently re-radiated as sound at frequencies where the modal damping is small. The coherent power plots of Figures 11 and 12 indicate the transmission of sound energy into the house is dispersive due to the frequency dependency of the transmission and not simply pure delay. The peak re-radiated sound pressure level has been found at 65 Hz for House #8 which corresponds to a very lightly damped mode as is shown in Table 2. The maximum instantaneous vibration levels have been found to be in the 8-20 Hz band corresponding to the two lowest frequency modes in Table 2.

Whether or not the structural modes listed in Tables 1 and 2 will be excited under impulsive, acoustic loads depends on the frequency distribution of the impulse energy impacting the structure. Figure 9 depicts the actual energy distribution of a single impulse recorded during a period which was described to be highly annoying, a time when the turbine was operating at 35 rpm. It should be noted the major spectral peaks of Figure 9 reside at 10.8 and 25.1 Hz both of which correspond to the broad 8-12 and 26 Hz modes in Table 2. Thus, the positioning of these spectral peaks and their respective amplitudes are very important in determining what modes may be excited and contribute to the coherent generation of both sound and vibration levels. Using pulse analysis techniques and a typical, average sound pressure frequency distributions for 35 and 23 rpm spectra, a list of the preferred spectral peak frequencies has been determined and is listed in Table 3. It is interesting to note that many of the structural resonances found in Homes #7 and #8 agree quite closely with four frame test houses used as part of sonic boom and aircraft fly-over noise investigations (ref. 7).

DISCUSSION AND CONCLUSIONS

The lowering of the turbine rotational speed from 35 to 23 rpm, as is indicated in Table 3, primarily results in a shifting of the preferred spectral peaks to lower frequencies. From pulse anal-considerations, the relative distribution of energy or the positioning of spectral peaks of such energy is controlled by the pulse width or duration. The repetition frequency,or blade-passage frequency in this case (which is determined by the rotational speed) has very little effect. A typical pulse width for a series of short impulses at 35 rpm typically lasts about 100 msec and increases to 123 msec at 23 rpm. The relative distribution of energies or peak amplitudes is determined by the combination of peak value or overpressure and the risetime; i.e., riserate. Thus the downward shift in frequency and the reduction in peak energies in some of the higher frequency modes is due to:

1. the increased residence time of the blade in the tower leg wake which increases the pulse duration, and
2. the reduction in the peak overpressure is due to a smaller aerodynamic loading of the blade as a result of the slower rotational speed and decreased static lift and therefore smaller maximum values to interrupt by a still undefined unsteady aerodynamic process.

The magnitude of the riserate, when viewed in terms of unsteady aerodynamics, reflects the change in lift above static values due to rapid, local attack angle fluctuations (refs. 5 and 6). Thus the pressure-time history of the acoustic signals may be thought to indicate the characteristics of the rapid changes in blade loads (and therefore in acoustic radiation) as the blade cuts through intense horizontal velocity gradients in the wake of the tower legs. The existence of such intense gradients has been verified by hot-wire anemometer measurements in a tower wake of similar dimensions belonging to a small wind turbine which is also capable of producing impulsive sounds under certain turbulent inflow conditions not yet fully understood.

The plot of peak overpressures against windspeed in Figure 10 suggests that some form of a bimodal process or forcing is taking place since it is possible for an impulse at a given rotational speed and wind velocity to assume either a higher or lower level separated by about 10 dB. Thus impulses which may not be causing any annoyance at one point in time may suddenly change levels at the same windspeed and begin to bother some homes. This has been observed to occur during the measurements of March 31, 1980. This would indicate stronger, transient velocity gradients are occassionally superimposed on the much weaker, mean velocity deficit flow field. Work by Sato and Kuriki (ref. 9) on the wake transition of a thin, flat plate in parallel uniform flow has shown the existence of three distinct subregions for transition regime flow. They found the intensity of the velocity fluctuations in a wake could be amplified exponentially when artificial excitation at predominant shedding frequencies was introduced in what they describe as the linear and nonlinear transitional subregions. If true for a cylinder, this excitation could be a predominance of turbulent eddies in the inflow whose dimensions correspond to a frequency near the Strouhal shedding frequency of the tower legs. This possibility has not been able to be confirmed with the MOD-1 due to the upper frequency response limitations of the wind sensing equipment, but visual evidence in comparing the impulse and turbulence characteristics does indicate some connection. Since the small wind machine at Rocky Flats exhibits some of the same characteristics, hot-film measurements of the inflow and wake regions will be undertaken in the near future to examine this hypothesis.

From the above discussion and the observations of Figure 9, the impulses being generated in the tower leg wake must be the result of time-dependent velocity gradients and not just a pure deficit since by definition such a deficit should be only a function of the upstream velocity. The MIT calculations have shown impulse-type sound pressure fluctuations can be predicted by using a mean wake as determined from wind tunnel tests, but the model fails to reproduce the important rapid riserates observed. What is important, however, is the model confirms impulses can be produced by the tower wakes (ref. 2) but a more realistic velocity distribution is necessary to reproduce the actual observations.

In summary, the following conclusions are drawn from the analysis of the collected acoustic and structural data:

1. The primary source of annoyance of nearby residents are the short bursts of acoustic energy associated with impulses being generated by a yet-to-be-defined unsteady aerodynamic process. This process involves the turbine blade interaction with a transient level of wake instability and resulting intensity of velocity fluctuations and horizontal gradients in the wakes of the legs.

2. The impulses are propagated entirely through an airborne path and subjected to atmospheric refraction effects which can enhance (or suppress) the level over normal, geometric spreading due to strong vertical and horizontal gradients of wind velocity and atmospheric thermal parameters.

3. The primary annoyance mechanism in the houses affected is the coupling of low-frequency impulse energy to lightly damped structural modes and the resulting vibration and re-generated acoustic emissions at the excited modal frequencies. From all appearances, the annoyance generated in House #8 is composed of a coherent excitation of low-frequency vibration at the 8-10, 14, and 26 Hz frequencies simultaneously with audible acoustic radiation at 60 and 65 Hz.

4. The potential for annoyance appears to be greater for House #7 due to the poorer acoustic absorption or increased transmissivity and the number of lightly damped structural modes.

5. From the evidence compiled to date, the only sure way to stop the annoyance under all conditions is to prevent any impulses generated from reaching annoying levels. This would mean reducing the tower wake velocity gradients to a point where the result would be similar to the spectral pressure-time plots of Figures 2 and 3. From the evidence at hand, it is necessary to destroy the organized, two-dimensional vortex flows thought to be developing in the lee of the tower legs by some form of aerodynamic spoiling device.

ACKNOWLEDGEMENTS

The cooperation and assistance of the NASA Wind Energy Project Office, the General Electric Company, and the Blue Ridge Electric Membership Corporation is gratefully acknowledged. Special thanks are given to the residents of Boone, North Carolina and specifically the residents near the MOD-1 who aided us in this investigation. The efforts of the SERI staff: Ed McKenna, Carol Etter, Dick Garrelts, Stan Thues, Chris Linn, Bob McConnell, and Jane Ullman contributed significantly. Ben Bell is acknowledged for his development of the time domain analysis program. The work was supported by the DOE Wind Energy Systems Division.

REFERENCES

1. Balombin, J.R.: An Exploratory Survey of Noise Levels Associated with a 100 kW Wind Turbine. NASA TM-81486, Lewis Research Center, Cleveland, OH. 1980.

2. Martinez, R., S.E. Widnall, and W.L. Harris: Predictions of Low-Frequency Sound from the MOD-1 Wind Turbine. FDRL Report No. 80-5, Massachusetts Institute of Technology. 1980, 77p.

3. Thomson, D.W.: Analytical Studies and Field Measurements of Infrasound Propagation at Howard's Knob, NC. Department of Meteorology, The Pennsylvania State University. 1980, 36p.

4. Homicz, G.F., and A.R. George; Broadband and Discrete Frequency Radiation from Subsonic Rotors. Journal of Sound and Vibration, Vol. 36 (2), 1974, pp 151-177.

5. Wright, S.E.: Discrete Radiation from Rotating Periodic Sources. Journal of Sound and Vibration, Vol. 17(4), 1971, pp 437-498.

6. Ericsson, L.E. and J.P. Reding: Unsteady Airfoil Stall Review and Extension. Proceedings of AIAA 8th Aerospace Sciences Meeting. AIAA Paper No. 70-77, New York, NY, 1970, 10p.

7. Carden, H.D. and W.H. Mayes: Measured Vibration Response Characteristics of Four Residential Structures Excited by Mechanical and Acoustical Loadings. NASA TN D-5776. Langley Research Center, Hampton, VA. 1970, 59p.

8. Bendat, J.S. and A.G. Piersol: Engineering Applications of Correlation and Spectral Analysis. Wiley (New York), 1980, p. 68.

9. Sato, H. and K. Kuriki: The Mechanism of Transition in the Wake of a Thin Flat Plate Placed Parallel to a Uniform Flow. Journal of Fluid Mechanics, Vol. 11, 1961, p. 351.

TABLE 1

MAJOR NORMAL AND COUPLED STRUCTURAL MODES OF HOUSE #7

Frequency (Hz)	Floor Modal Damping Characteristics			Window	
	Vert	Horiz	Cross	Mode Damping	Cross[a]
8.6*	L[b]	M	M[c]	M	M
20	M	L	S	L	S+
30	L	VL	S+	M	S+
59	L	M	M	L	M
79	L	M	M	L	M
89	VL	M	S	L	S
96	VL	M	M	M	M

TABLE 2

MAJOR NORMAL AND COUPLED STRUCTURAL MODES OF HOUSE #8

Frequency (Hz)	Floor Modal Damping Characteristics			Window	
	Vert	Horiz	Cross	Mode Damping	Cross
8.9*	L	L	S	VL	S+
14	L	L	S		
21	M	L	S		
26	L	L	S		
32				L	W
50	VL	VL	S+	L	M
60	VL	VL	S+	L	S+
65	L	VL	S+		

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*estimated to be house fundemental resonant frequency

[a] Cross coupling with floor vibrations

[b] Damping: VL = very light, L = light, M = moderate

[c] Degree of cross-coupling: W = weak, M = moderate, S = strong

TABLE 3

PREFERRED SPECTRAL PEAKS FOR TYPICAL IMPULSES

35 RPM

Frequency (Hz)	Relative Level (dB)
6.25	0
16.25	-9
26.25	-23
45.0	-39
62.5	-47
81.3	-51
97.3	-55

23 RPM

Frequency (Hz)	Relative Level (dB)
4.4	0
10.6	-9
17.5	-15
25.6	-29
30.6	-38
38.8	-44
51.9	-47
65.0	-55

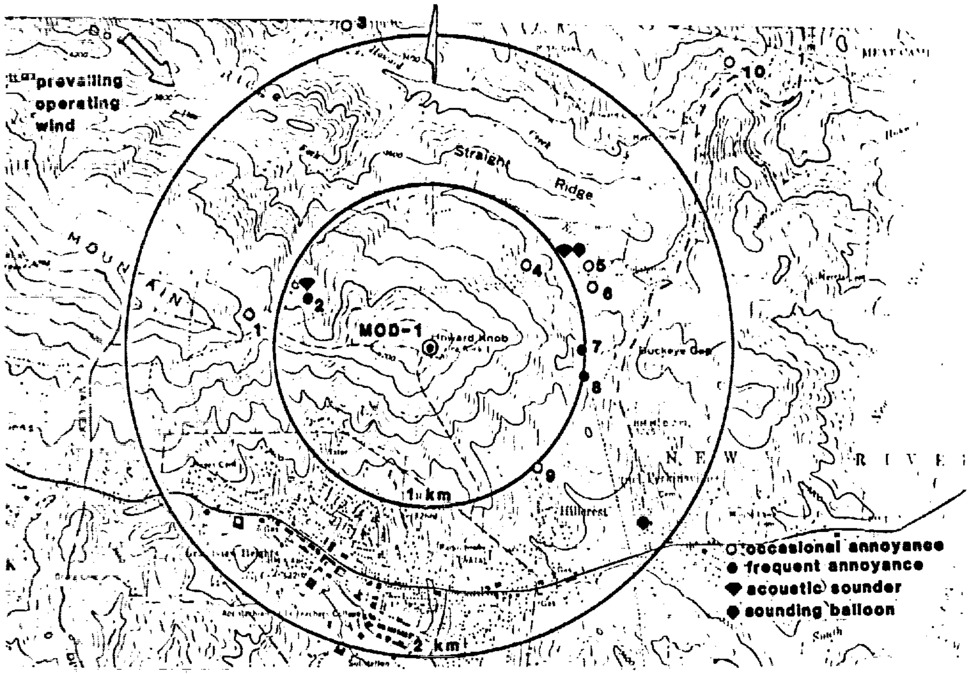

Figure 1. Map showing area surrounding MOD-1, complainant homes, and location of atmospheric measuring equipment for March 1980 test series.

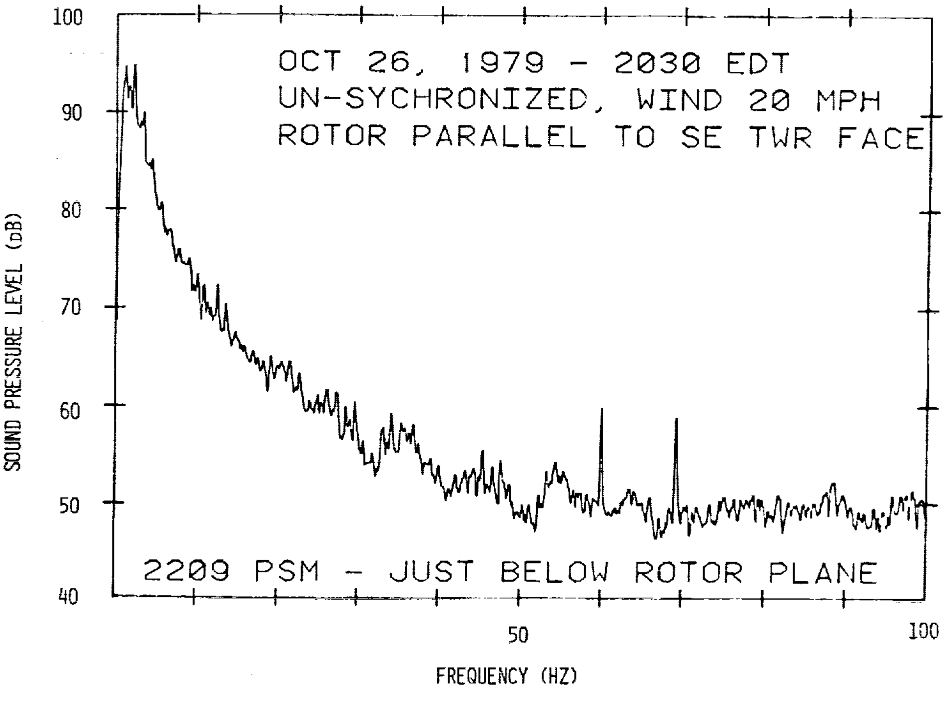

Figure 2. Sound pressure spectrum of MOD-1 acoustic emission with no impulse present.

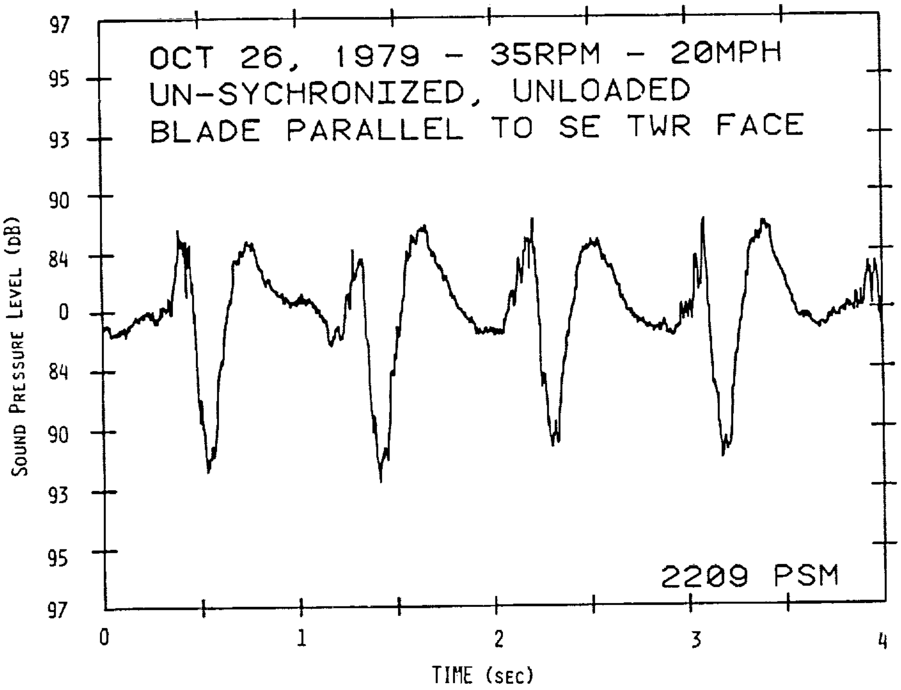

Figure 3. Pressure-time history of acoustic signal of Figure 2. Two complete rotor revolutions.

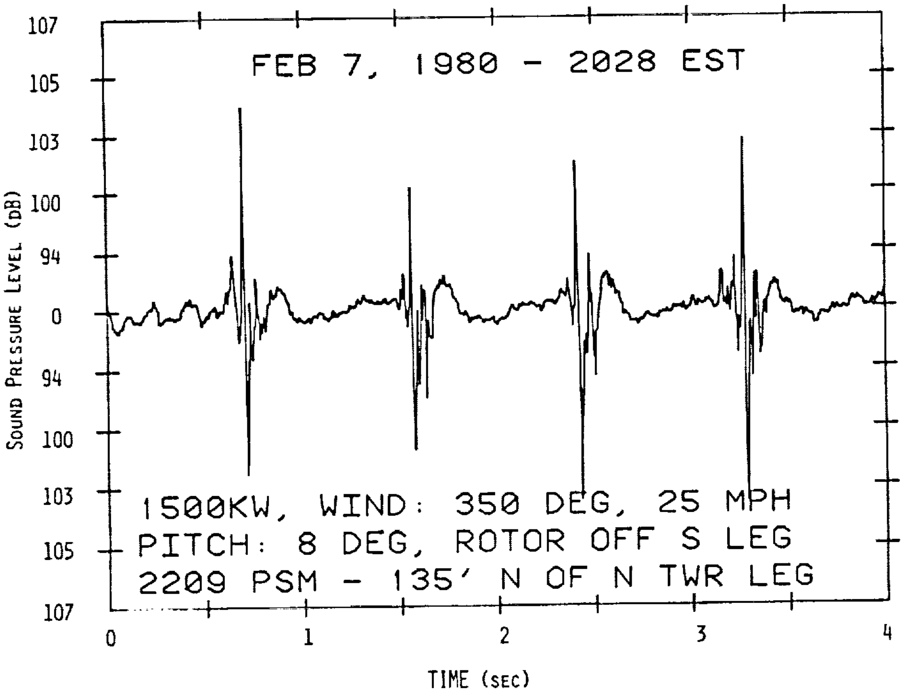

Figure 4. Pressure-time history of strong impulses. Two complete rotor revolutions.

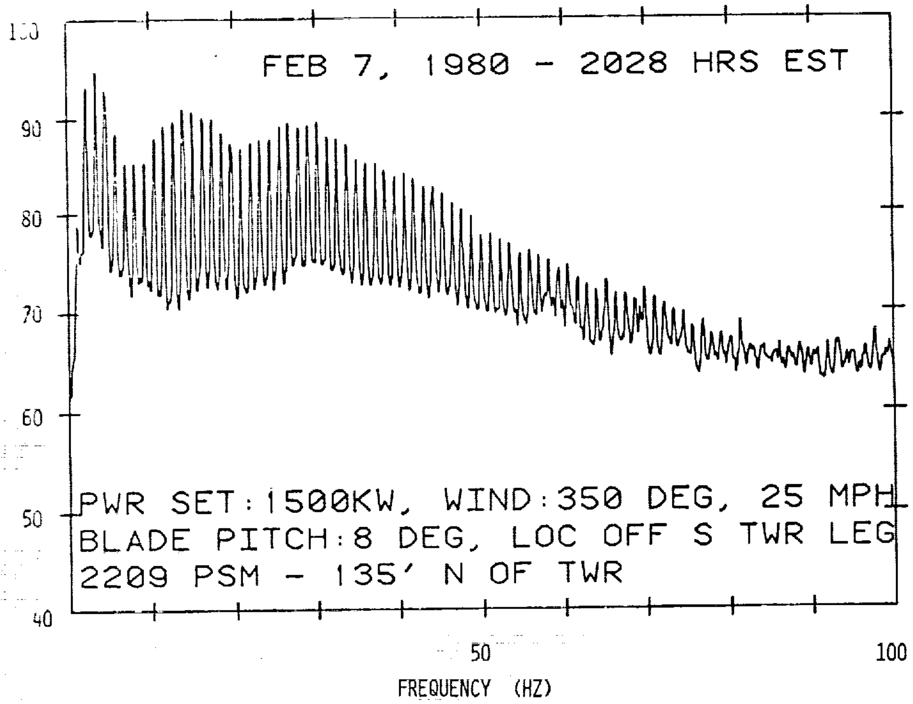

Figure 5. Sound pressure spectrum of MOD-1 acoustic containing strong impulses of Figure 4.

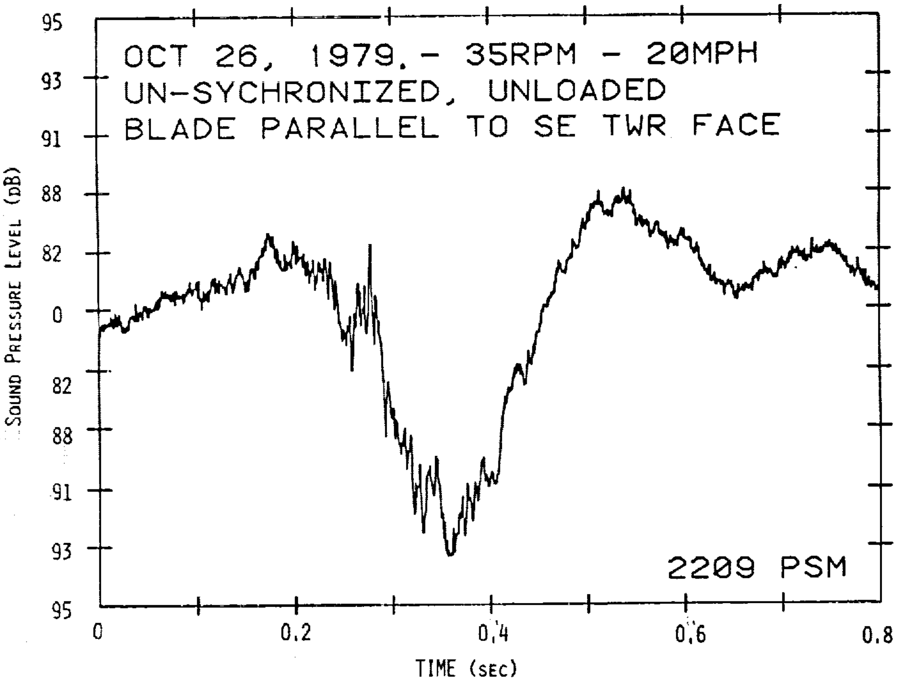

Figure 6. Detail of pressure-time history of Figure 3 for a single blade passage by the tower.

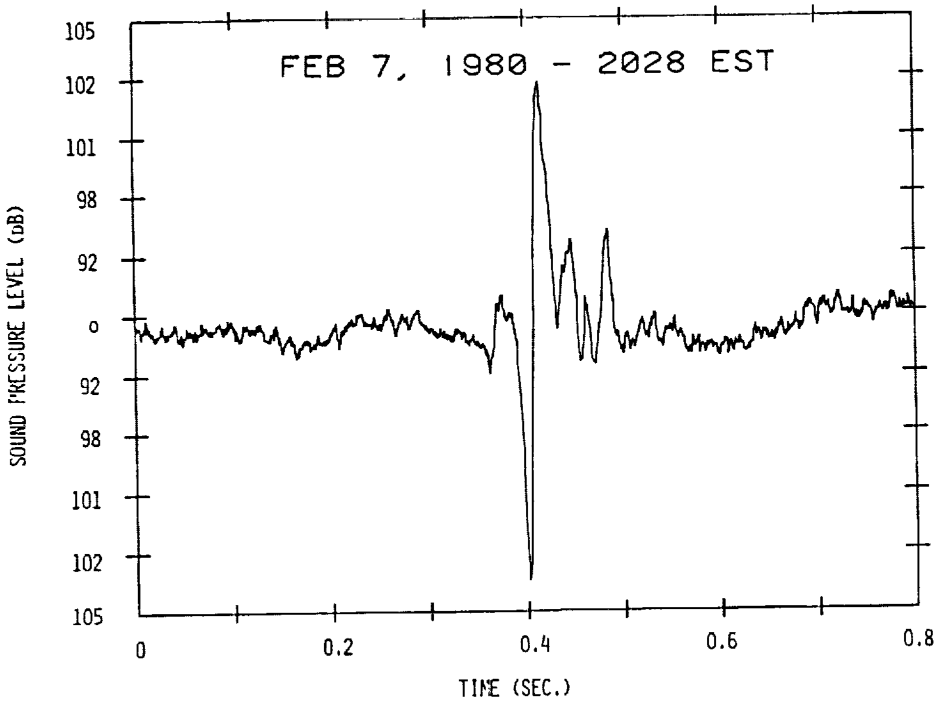

Figure 7. Detail of pressure-time history of Figure 4 for a single blade passage by the tower.

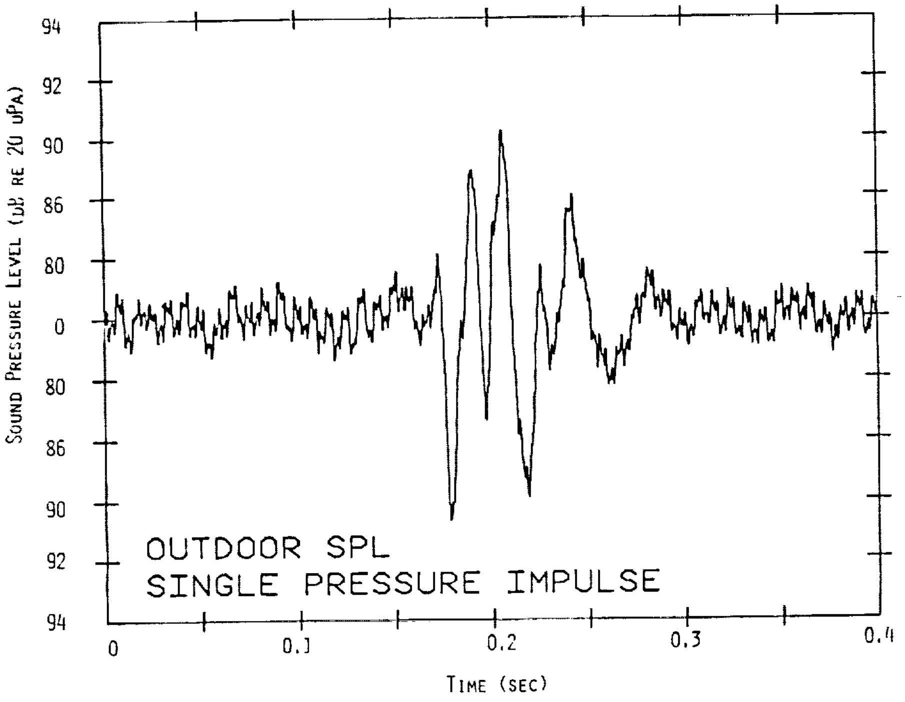

Figure 8. Far-field pressure-time history of strong impulse received at House #8 on March 31, 1980.

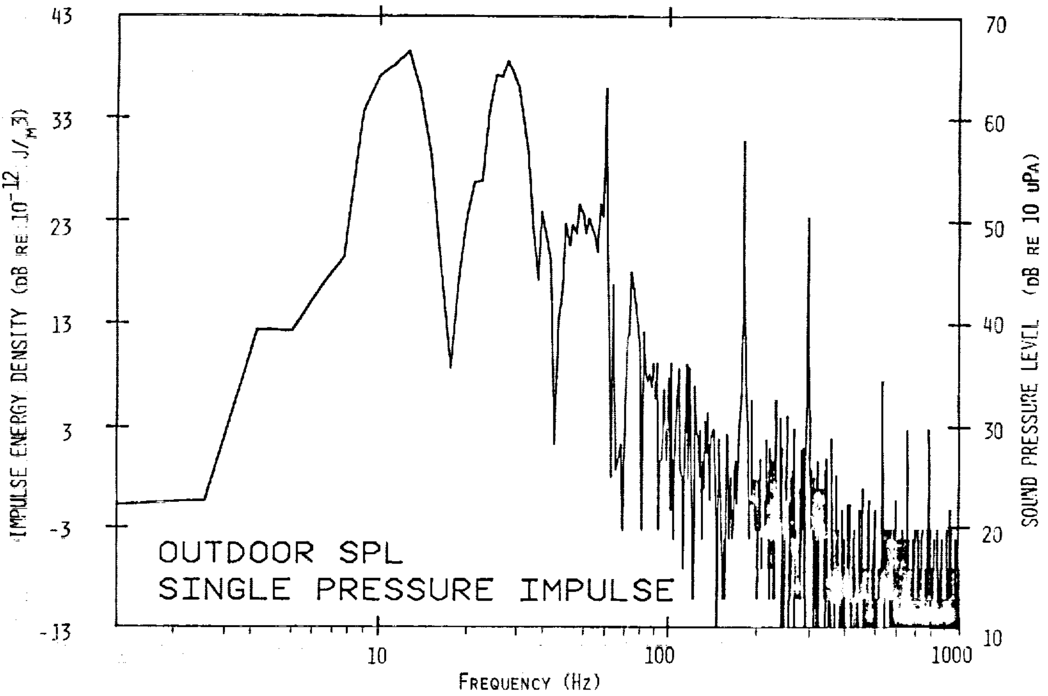

Figure 9. Energy distribution of single impulse of Figure 8 received at House #8.

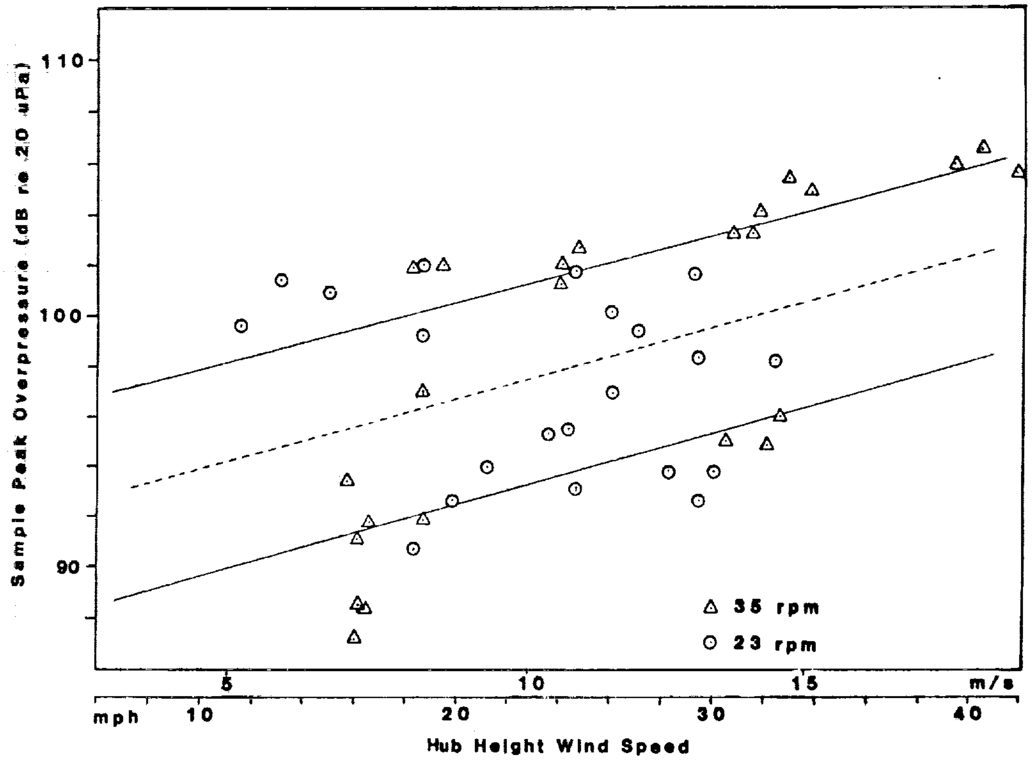

Figure 10. Plot of sample peak impulse overpressure versus windspeed in acoustic near-field.

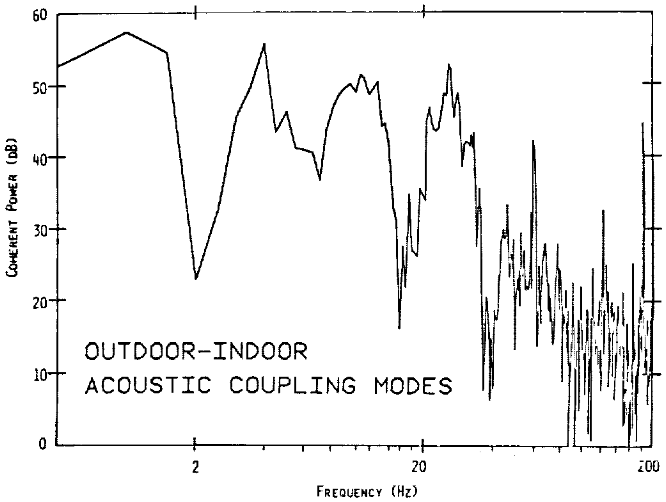

Figure 11. Plot of direct acoustic coupling to the interior of House #7.

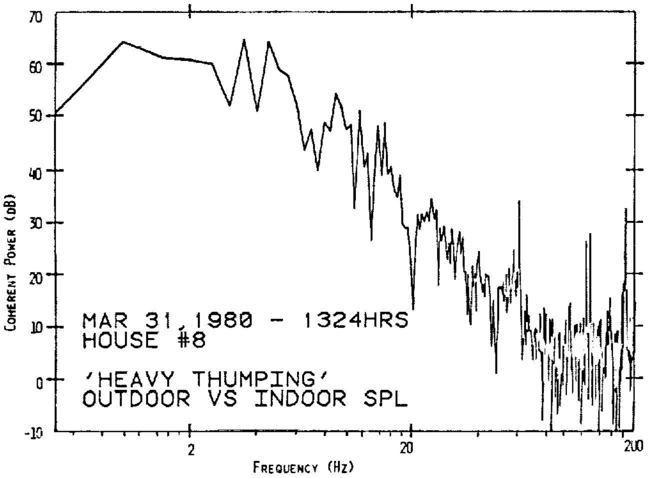

Figure 12. Plot of direct acoustic coupling to the interior of House #8.

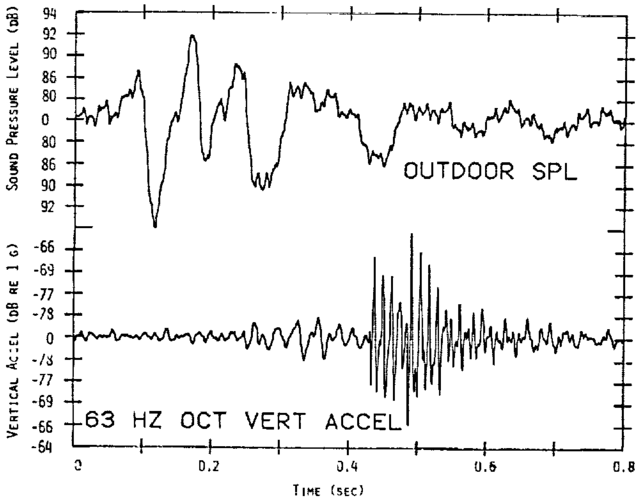

Figure 13. Example of time delay in forced vibration (and acoustic emissions) due to impulsive acoustic loading of House #8.

QUESTIONS AND ANSWERS

N.D. Kelley

From: Anonymous

Q: Were you able to correlate some of your data scatter to any gust intensity measurements?

A: *Only qualitatively. We have made some attempts at this with mixed results. We suspect the answer lies in turbulent eddies whose dimensions are close to the equivalent Strouhal shedding frequencies of the tower legs. The available wind data does not reach these frequencies.*

From: W.K. Wentz

Q: What is the future of large downwind rotors?

A: *I believe the downwind rotor is still viable if the tower wakes can be smoothed sufficiently to preclude the generation of large amounts of noise, particularly impulse noise.*

From: F.W. Perkins

Q: Is the time delay between excitation and response of a house related to house dimensions?

A: *I do not know. I refer the questioner to the work by Carden and Hayes at NASA Langley on aircraft sonic boom and fly-over noise.*

From: P.M. Abbot

Q: At 23 rpm, 10 mph, the SPC was over 100 lbs and higher than for 35 rpm. Is reduction to 23 rpm a solution to the problem?

A: *No, not entirely, only control of the tower leg wake appears to offer a complete solution.*

From: G.P. Tennyson

Q: Has there been found any similarity to the Smith Putnam noise experience?

A: *I am not aware of any such information. I have heard local residents who were living there at the time say that it was not noisy.*

From: P.M. Moretti

Q: Is there a correlation of the noise to the exact wind direction?

A: *Yes, we believe this is due to the propagation, machine orientation, and terrain.*