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ACOUSTIC TESTS OF THE MOD-0/5A WIND TURBINE
ROTOR WITH TWO DIFFERENT AILERONS

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INTRODUCTION

Partial span ailerons have been proposed for a large horizontal axis wind turbine (MOD-5A) as an alternative to full or partial span blade pitch to control lift and drag at above rated output power. Two configurations of ailerons being considered for application to the proposed MOD-5A wind turbine generator were available at reduced scale for testing on the MOD-0 machine at the NASA Plumbrook test site. This paper presents some basic parametric acoustic data for these two aileron configurations and shows appropriate comparisons.

This effort is part of the Department of Energy wind energy program which is managed by the NASA Lewis Research Center. The rotor blades which were tested on the MOD-0 machine closely model those proposed for the larger MOD-5A machine and were designed and furnished by the General Electric Company.

APPARATUS AND METHODS

Description of Site

The wind turbine site at which noise measurements were made is at the NASA Plumbrook facility located near Sandusky, Ohio (Figure 1). The terrain in the measurement area is essentially flat, and devoid of trees and bushes. The ground surface was covered with approximately six inches of snow for the first aileron test and was grass covered for the second test. In both instances background noise levels were very low except for the occasional passage of automobiles and aircraft.

Description of Wind Turbine

The MOD-0 wind turbine has a two bladed 39 m (128 ft) diameter rotor mounted on a 36.6 (120 ft) high tower with a twelve sided cross section.

The distance across the tower, between flats, is 2.1 m (7 ft) at the base and tapers to 1.5 m (5 ft) at the top. The rotor of the MOD-0 is downwind of the supporting tower, operates at 40 rpm and is nominally rated at 200 kW. In an attempt to simulate the proposed MOD-5A (upwind design) angles of attack, the MOD-0 machine was operated at 20 rpm and power was limited to 35 kW which is achieved at a wind speed of 4.5 m/s (10 mph).

Two different partial span aileron configurations (Figure 2) were tested. The plain aileron pivots at 38% of the blade chord. The balanced aileron also pivots at 38% of the chord, but extends to about 50% of the chord on the high pressure side of the blade. In both cases the ailerons were fitted to the outer 6.6 m (21.6 ft) of each blade. Blades tapered in chord from about 1.22 m (6 ft) at the inboard aileron station (NACA 64624 airfoil) to about 0.65 m (2.1 ft) at the tip aileron station (NACA 64615) and likewise the twist varied from 3° to 1°. The rotor blades have a total area of about 26.8 m^2 (288 ft^2), and have roughness strips extending from the nose of the airfoil to about 5% chord on both surfaces. Data were taken at a rotational speed of 20 rpm for both aileron configurations and also at 13.8 rpm for the plain aileron.

Wind Turbine Operating Conditions

Data for the plain aileron were recorded on 17 and 19 January 1984 between 0900 and 1600 hours. The temperature range was -12 to -5°C and the mean wind velocity, V, ranged from about 3 to 6 m/s (7 to 13 mph). Data for the balanced aileron were recorded 11-13 June 1984, the temperature range was 21 to 29°C and the mean wind velocity ranged from 2 to 5 m/s (5 to 12 mph).

Wind velocity and direction were monitored and continuously recorded from meteorological instruments located at the height of the rotor hub and 60 m upwind of the machine. Example time histories of wind velocity and direction and electrical power output are shown in Figure 3. The variations indicated in Figure 3 are representative of those existing at the times of the tests for which data are reported herein.

Noise Measurements

All noise measurements were made with commercially available battery powered instrumentation. One-half inch diameter condenser microphones with a usable frequency range of 3-20,000 Hz were used with an FM four channel recorder which provides a dynamic range of about 40 dB in the frequency range of 0 Hz to 15,000 Hz. For some recordings the microphone signals were C-weighted in an attempt to more effectively use the available dynamic range.

The measurement locations for these tests are shown in Figure 4. Data were obtained at a distance, r, of 57 m (191 ft) and at various azimuth angles: 0° (on-axis upwind), 90° (crosswind right), 180° (on-axis downwind) and 270° (crosswind left). Spectral data were obtained with the aid of conventional one-third octave band and narrow band analyzers.

To minimize the detrimental effects of wind noise, polyurethane foam microphone wind screens were used and microphones were placed at the ground surface, where wind velocities were relatively low.

While acoustic signals were being recorded on two tape recorder channels, simultaneous recordings of time code and rotor blade position were made on the other two tape recorded channels. These latter data were used as an aid in acoustic data analyses.

RESULTS AND DISCUSSION

Acoustic data are presented first for the plain aileron and then for the balanced aileron. Effects that are examined include power output, directivity and aileron deflection angle.

Plain Aileron

Effects of Power Output - The effects of output power, P, on generated noise are shown in Figures 5 and 6. Narrowband spectra are presented for the upwind measuring station and an aileron deflection angle of 5°. The solid and dotted curves correspond to output power conditions of 35 KW and 3 KW respectively. Figure 5 indicates that at low frequencies the higher noise levels are associated with the higher output power condition. The higher frequencies (Figure 6) are associated with the blade boundary layers and trailing edge flows and are apparently not strongly affected by an increase in output power. The spectra are largely random in nature with a few identifiable discrete frequency components. Those at 30, 60 and 90 Hz are associated with the electrical generator and the closely spaced harmonics below 30 Hz are apparently due to blade/tower wake interactions.

Effects of Tower Wake - It is known from measurements made on other downwind machines that the wake from the tower affects the generated noise. By using the blade position indicator as a trigger signal it was possible to analyze acoustic data for those times when the rotor blades were approximately horizontal, thus removing the effect of the tower wake. It was concluded from comparisons of these data with those presented in Figures 5 and 6 that the tower wake was responsible for the harmonics visible below about 30 Hz. The remainder of the spectrum was apparently unaffected.

Directivity Effects - Comparisons of the measured spectra at three different locations are shown in Figures 7 and 8, in the form of narrow band and one-third octave spectra respectively. The main differences are noted in the frequency range 400 to 1600 Hz. Downwind and crosswind levels are generally higher than upwind levels.

Effects of Aileron Angle - Spectra corresponding to different aileron angles, α, are shown in Figures 9, 10 and 11. Figure 9 illustrates the change in the upwind noise spectrum as the aileron angle changes from 0° to 15°. Note that broad peaks develop in the frequency range 400-800 Hz and the peak noise levels increase as aileron angle increases up to a maximum of 12°. As the aileron angle is further increased the peak noise levels decrease.

These peaks have been analyzed in detail and are determined to be of aerodynamic origin. The nature of these peaks and other details of the spectra are illustrated in the narrow band data of Figures 10 and 11.

For the conditions where resonant peaks exist in the spectra a howling noise is observed which dominates the other noises from this machine. As aileron angle increases there is a reduction in the frequency of the howling (see Figure 9). This behavior suggests that the source mechanism may be an edge tone phenomenon involving some combinations of upstream and downstream edges of the blades, ailerons, and/or cavities associated with the counterweight mechanisms.

The noise peaks probably result from resonating cavities in the blade, driven by edge tones. Such a mechanism is velocity sensitive and would not necessarily be activated at other velocities. Note that howling did not exist at a lower rotational speed nor was it evident in wind tunnel tests of the non-rotating blade at lower section speeds.

The directional properties of the howling noise are indicated in Figure 11 which gives comparable spectra at two aileron angles for upwind, downwind, and crosswind locations. Noise level increases are seen to be the smallest in the downwind direction. This result is probably due to the fact that the disturbance creating the increased noise is on the upwind side of the blade and is thus shielded in the downwind direction.

The howling noise encountered on this aileron is believed to be configuration sensitive and thus might not occur for other aileron designs.

The edge tone noise components might however be present on any configuration having an open spanwise slot due to aileron deployment.

Effects of Rotational Speed - For a limited number of test runs the rotational speed of the machine was reduced from 20 to 13.8 rpm. Example data are shown in Figure 12. It can be seen that a reduction in rpm results in a general reduction in the noise levels of about 8 dB for the same power output. This reduction is consistent with that predicted for broadband noise due to the reduced tip speed. At 13.8 rpm no resonances can be seen in the frequency range 400-500 Hz. Note that the peaks in the low speed spectrum at frequencies between 800 and 1600 Hz are noises of mechanical origin and may not be associated with the wind turbine.

Balanced Aileron

Effects of Aileron Angle - Measured spectra for a range of aileron deflection angles and power values are shown in Figures 13 and 14. On-axis data are shown in both narrow band and one-third octave band form. The narrow band spectra of Figure 13 are included to show the character of the radiated noise. Note that the spectral components are generally random in nature with only a few relatively weak discrete frequencies present. The remaining data are presented for convenience in one-third octave band form.

Figure 14 contains spectra for tests in which the rpm was held constant and the aileron deflection angle was systematically varied. It should be noted that under some conditions the wind turbine was not generating power (deflection angles of 6° and 8° in Figure 14 b). Thus auxiliary power was supplied in order to maintain the rotor speed. In the upwind direction there is a trend toward higher noise levels at higher deflection angles, particularly in the frequency range 200-800 Hz. In the downwind direction there is very little effect of deflection angle except at frequencies below about 125 Hz. In other similar tests at higher deflection angles similar results were obtained.

Effects of Power - Measurements were made at fixed aileron deflection angles for ranges of wind speed and output power. As in the case of the plain aileron it was concluded that the noise levels of the low frequency components increased as power increased. The levels at high frequencies are relatively insensitive to power changes.

Directivity - Figure 15 presents one-third octave band spectra for measurements made in the upwind, downwind and crosswind directions. At frequencies below about 500 Hz the noise levels in the crosswind direction are lower than those on axis, whereas at higher frequencies no consistent differences are discernible. The dominant noise at low frequencies is due to blade loading fluctuations resulting from inflow turbulence. This noise component is expected to exhibit a dipole radiation pattern with its maximum on the axis of rotation. Such a pattern is consistent with the above observation.

COMPARISONS OF AILERON DATA

Direct comparisons of the data obtained for the plain and balanced ailerons are given in Figures 16 and 17. Figure 16 presents measurements made in both the upwind and downwind directions, for comparable operating conditions. There is a clear trend for the balanced aileron to produce higher noise levels than the plain aileron, particularly at freqencies below about 250 Hz. The above result is surprising because both configurations are nominally the same at $\alpha=0°$ except for small differences in the way the ailerons fair into the blade. These differences are presumed to be responsible for the higher frequency (above 400 Hz) sound levels being greater for the balanced aileron in the upwind direction. The downwind (low pressure) side of the blade is identical for both ailerons and the high frequency sound levels show good agreement for the two configurations. The differences in the noise levels at frequencies below 400 Hz in the upwind and downwind directions are considerable. Such a difference does not exist in the crosswind direction (Figures 8 and 15). It is expected that the dominant noise source in this frequency range is due to inflow turbulence, exhibiting a dipole radiation pattern, the highest noise levels being in the direction perpendicular to the rotor plane. This was observed for the balanced aileron (Figure 15), but not for the plain aileron (Figure 8). This implies that for the plain aileron test, noise due to inflow turbulence was at a lower level. Although atmospheric turbulence was not measured, the two tests were conducted under different weather conditions, and thus it can be inferred that the turbulence levels were higher for the balanced aileron test.

Comparisons of measured and predicted spectra for both the MOD-0A (40 rpm) and the MOD-0/5A (20 rpm) rotors are presented in Figure 17. Figure 17(a) shows the measured MOD-0A data from Reference 1 compared to predictions by the method of Reference 2, which incorporates empirical coefficients based on detailed data from one large machine (MOD-2). This prediction model includes contributions from the inflow turbulence, the turbulent boundary layers interacting with the trailing edges and the wakes due to trailing edge bluntness. Predicted values are in general agreement regarding both the slope as a function of frequency and the levels. Similar comparisons for the slower turning MOD-0/5A rotor in Figure 17(b) show the predicted levels to be lower than the measured values and furthermore the slopes of the measured and predicted curves do not agree. These data suggest that the empirical basis for predicting blade noise may not be applicable to blades with ailerons, or to blades operating at tip speeds markedly below approximately 80 m/sec or both.

CONCLUSIONS

Measurements of noise from a MOD-0 wind turbine equipped with two configurations of partial span ailerons, yielded the following conclusions:

1. Low frequency (below 100 Hz) noise levels increase with increasing power.
2. The interactions between the wind turbine blade and the tower wake produces discrete low frequency (below 30 Hz) noise components, but does not affect noise levels at other frequencies.
3. The deflection of the plain aileron results in greatly enhanced noise levels at 400-800 Hz, reaching a maximum at 12° aileron deflection. This increased noise is apparently due to flow induced resonances of cavities in the blade.
4. The deflection of the balanced aileron resulted in smaller increases in noise level relative to those for the plain aileron.
5. Enhanced noise levels due to aileron deployment are greater in the upwind than in the downwind direction.
6. At frequencies below about 400 Hz the noise levels associated with the balanced aileron are significantly higher than those for the plain aileron. This is believed due to differences in the structure of the atmospheric turbulence for the two tests rather than intrinsic properties of the ailerons.

REFERENCES

1. Shepherd, Kevin P. and Hubbard, Harvey H.: Sound Measurements and Observations of the MOD-0A Wind Turbine Generator NASA CR 165856, February 1982.

2. Grosveld, F. W., Shepherd, K. P. and Hubbard, H. H.: Measurement and Prediction of Broadband Noise from Large Horizontal Axis Wind Turbine Generators. Proceedings of DOE/NASA Wind Turbine Technology Workshop, Cleveland, OH, May 8-10, 1984. (Proposed NASA CP).

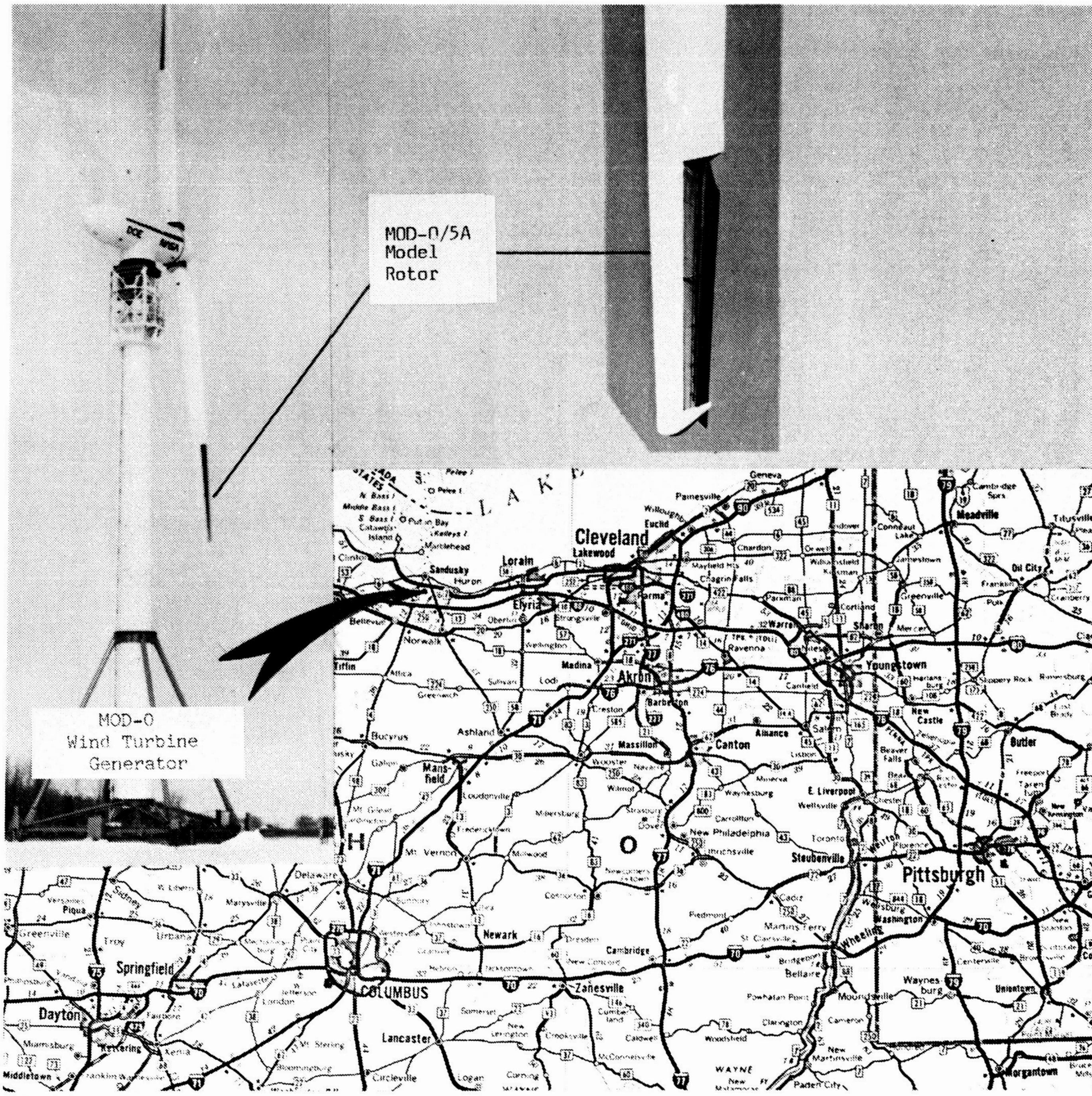


Figure 1. General Location of Test Site with Inset Photographs Showing MOD-0 Wind Turbine Generator and MOD-0/5A Model Rotor with Aileron

At 67% of Span (NACA 64624)

at 98% Span (NACA 64615) Illustrating 30° Deflections

(a) Plain Aileron

(b) Balanced Aileron

Figure 2. Cross Sectional View Sketches of the Rotor Blade Ailerons at Two Spanwise Stations.

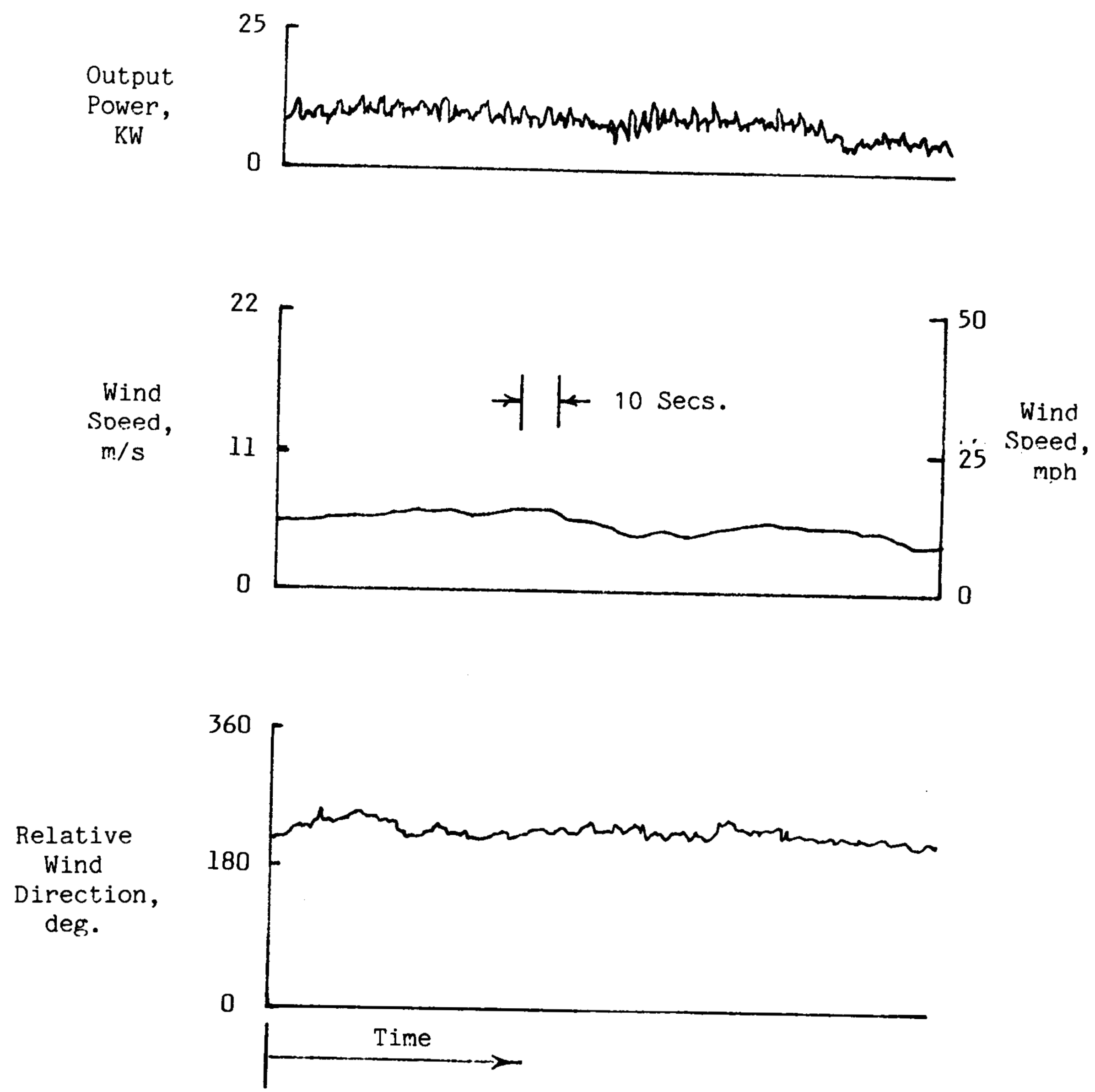


Figure 3. Simultaneous Traces of Oscillograph Recordings of Output Power, Wind Speed and Wind Direction for the MOD-0/5A Model Rotor for an Example Test Condition.

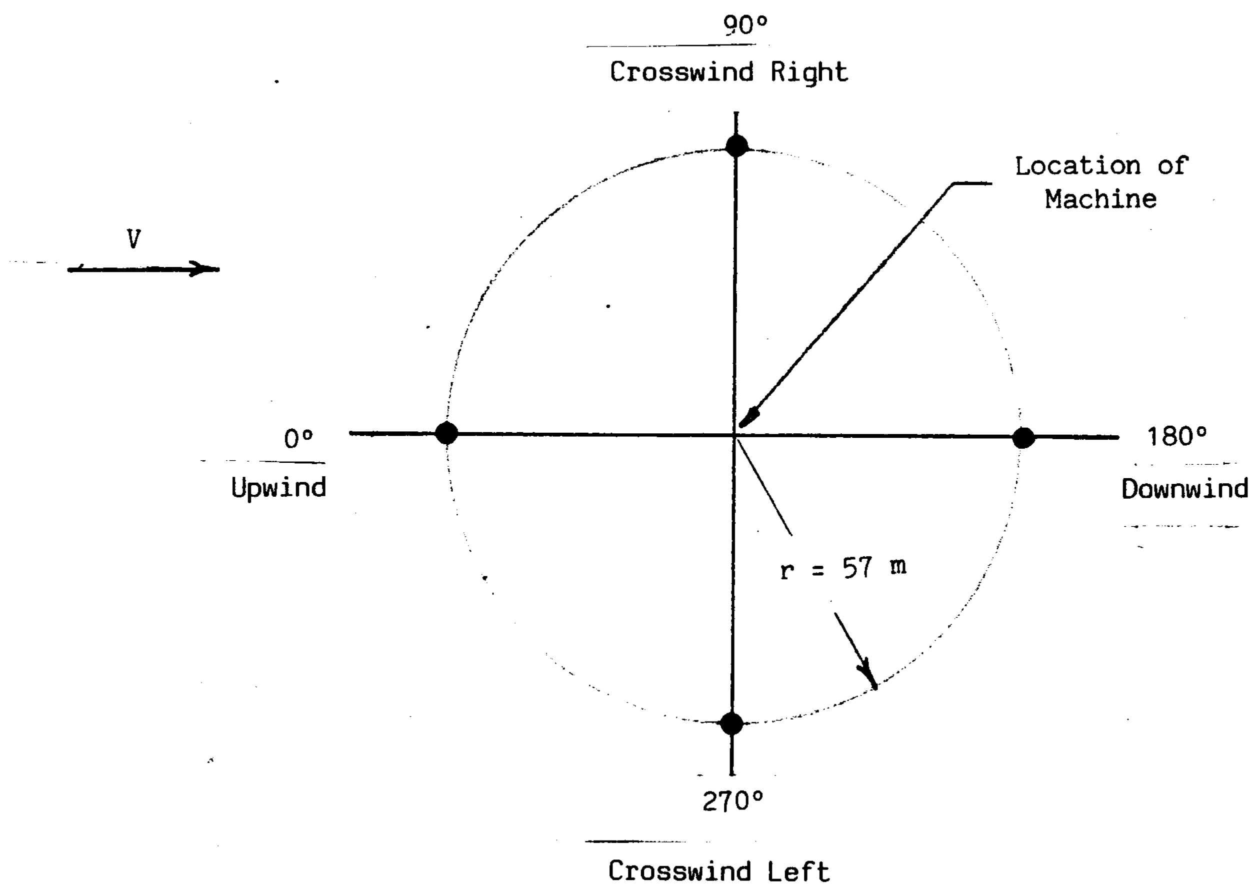


Figure 4. Plan View Sketch Showing Locations at which Data were Measured.

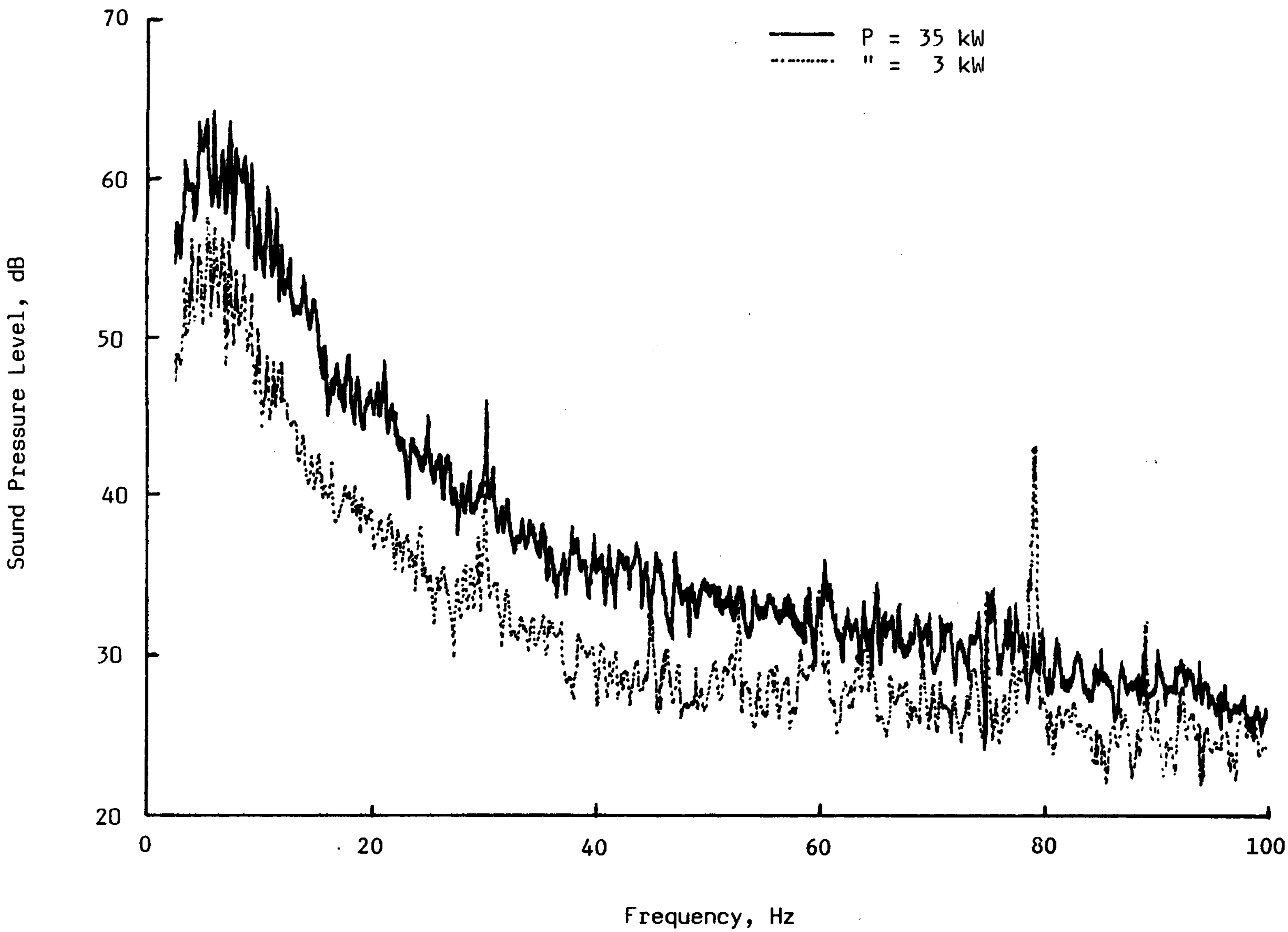


Figure 5. Effects of output power on the narrow band (Δf=0.125 Hz) noise spectra upwind of the MOD-0/5A rotor with plain aileron. α=5°; r=57m, V=3.6-5.8 m/s.

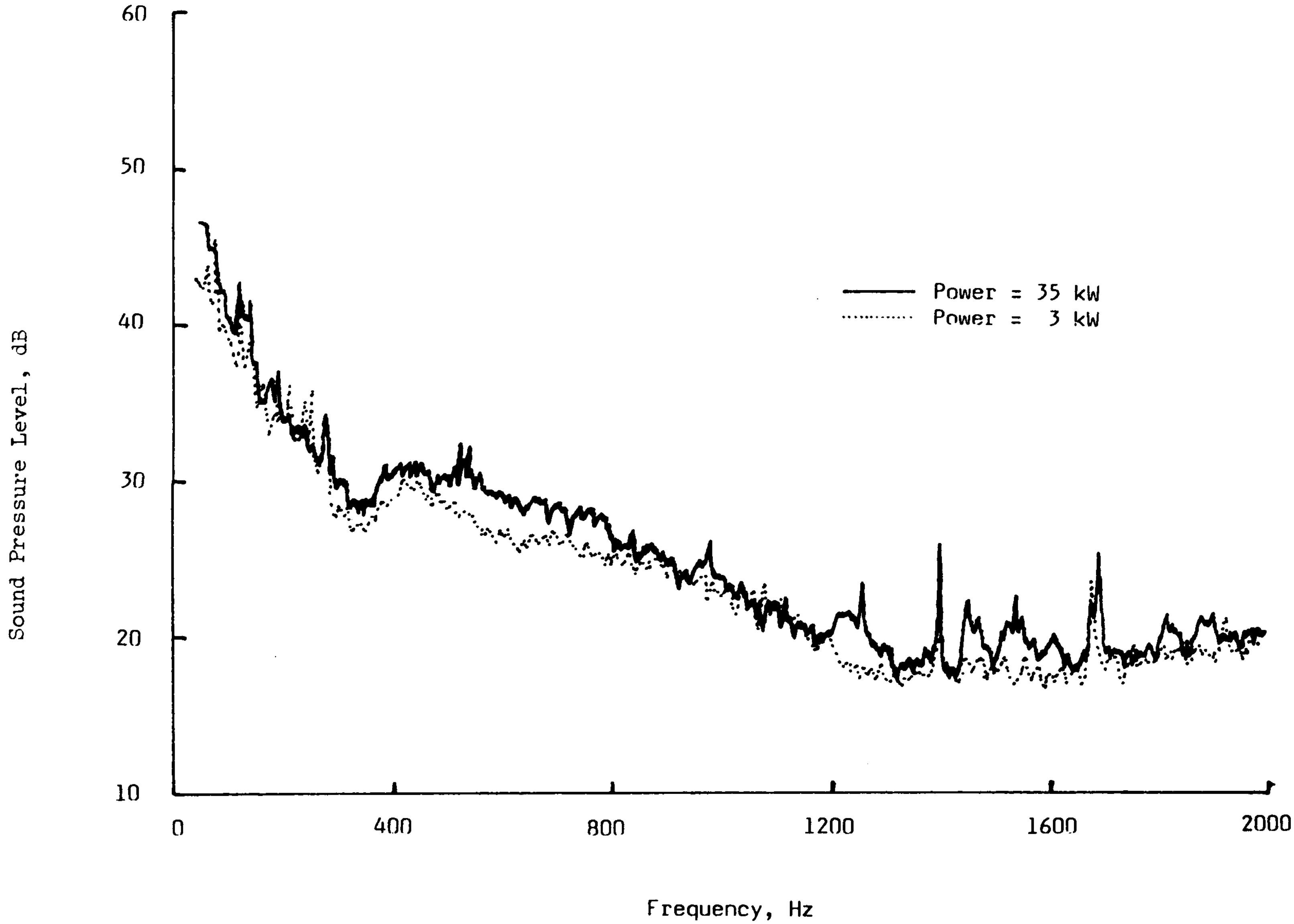


Figure 6. Effects of output power on the narrow band (Δf=2.5 Hz) noise spectra upwind of the MOD-0/5A rotor with plain aileron. $\alpha=5^{o}$, r=57m, V=3.6-5.8 m/s.

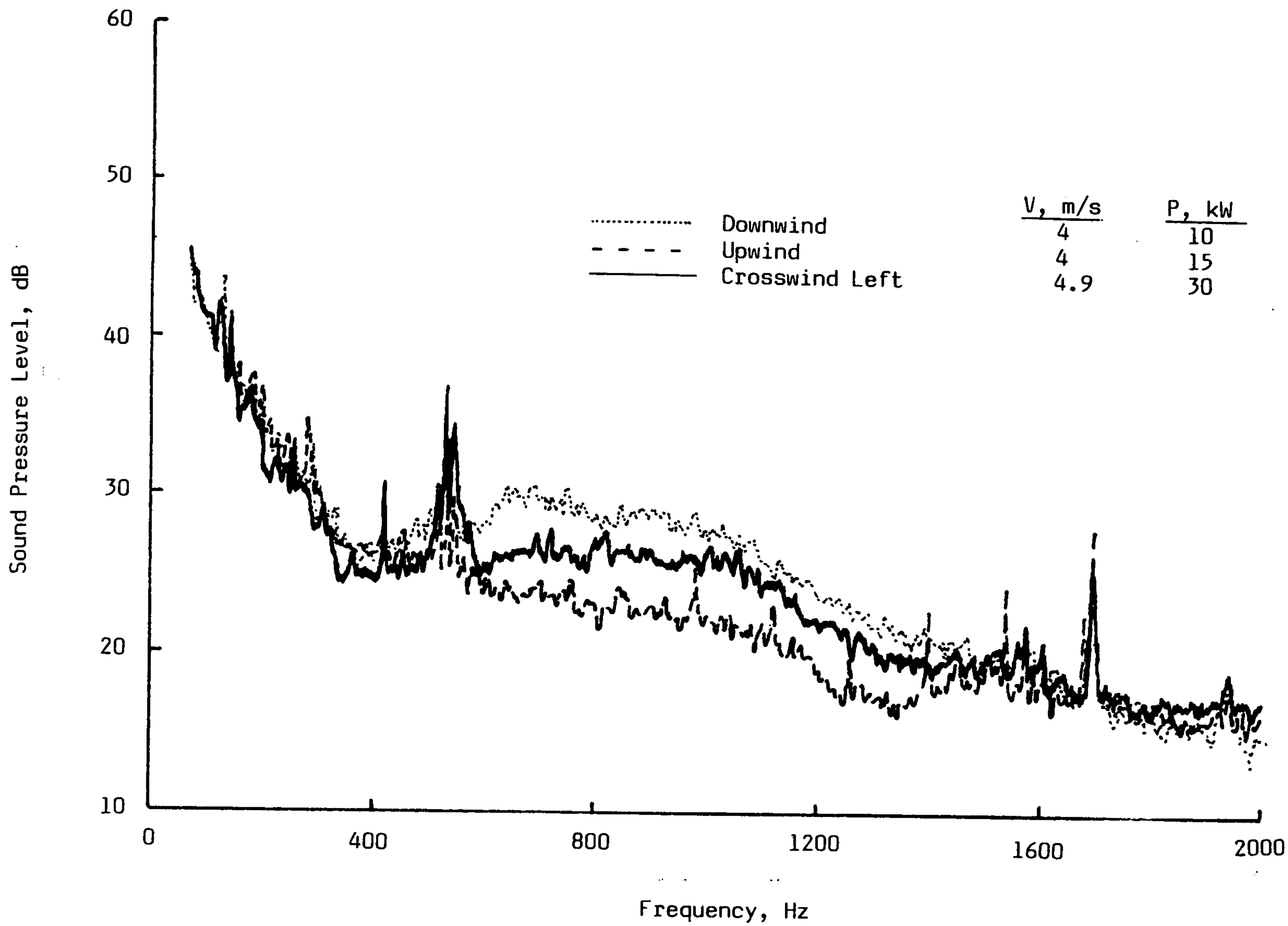


Figure 7. Narrow band (Δf=2.5 Hz) spectra of the noise from the MOD-0/5A rotor with plain aileron in three different directions. r=57 m , α=0°.

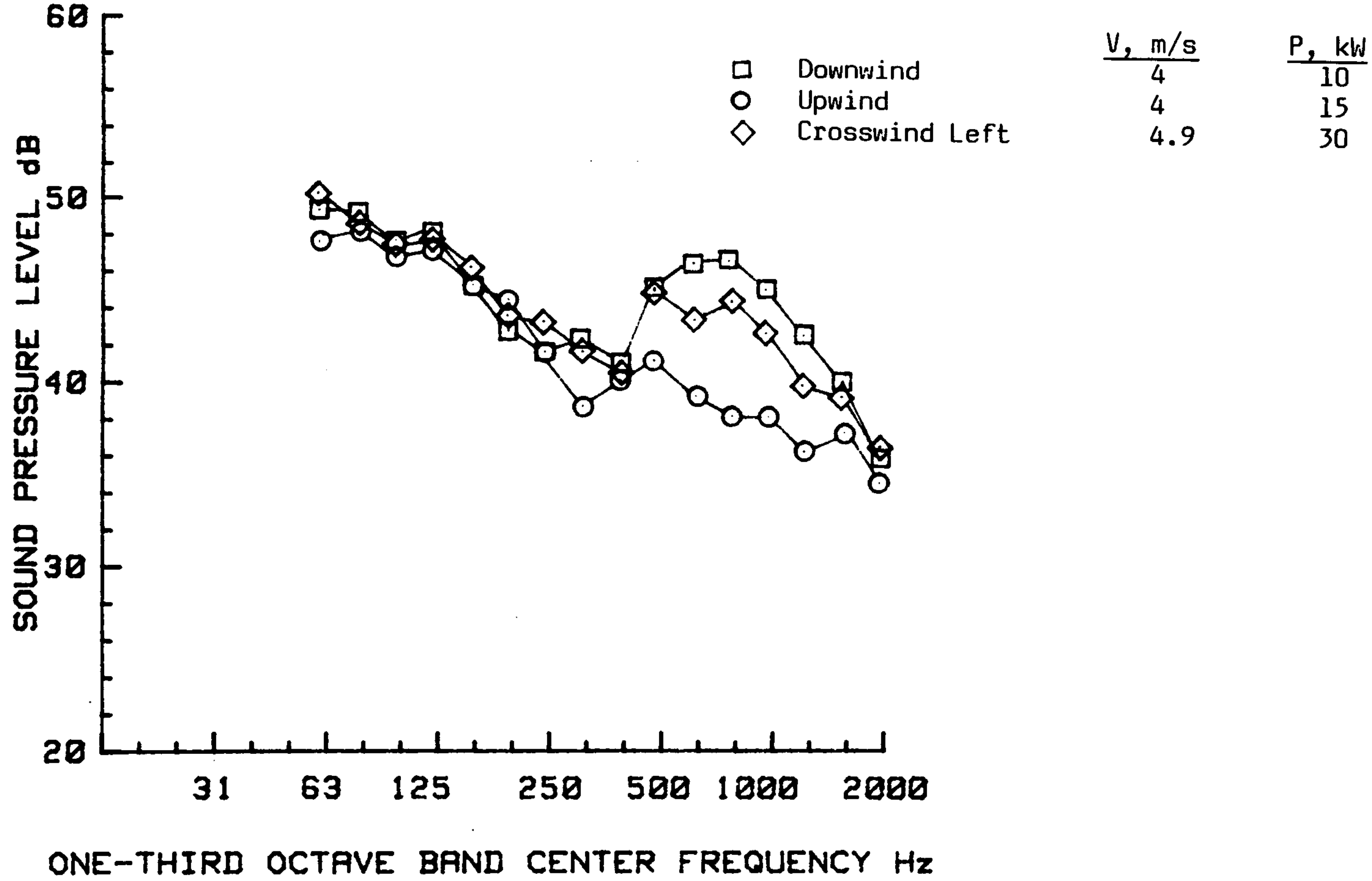


Figure 8 . One-third octave band spectra of the noise from the MOD-0/5A rotor with plain aileron in three different directions, r=57 m, $\alpha=0°$.

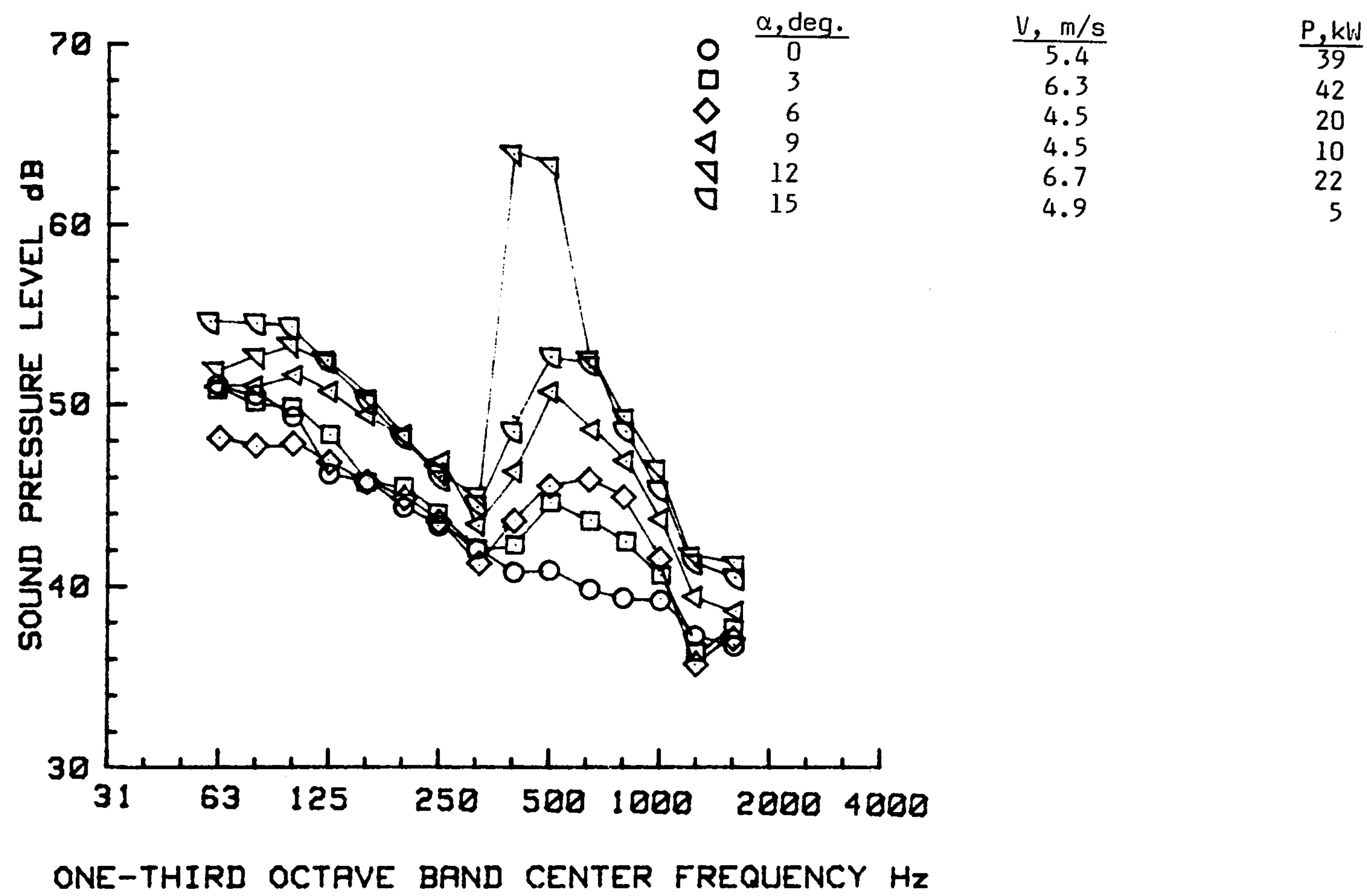


Figure 9. One-third octave band noise spectra measured upwind for a range of deflection angles of the plain aileron. r=57 m.

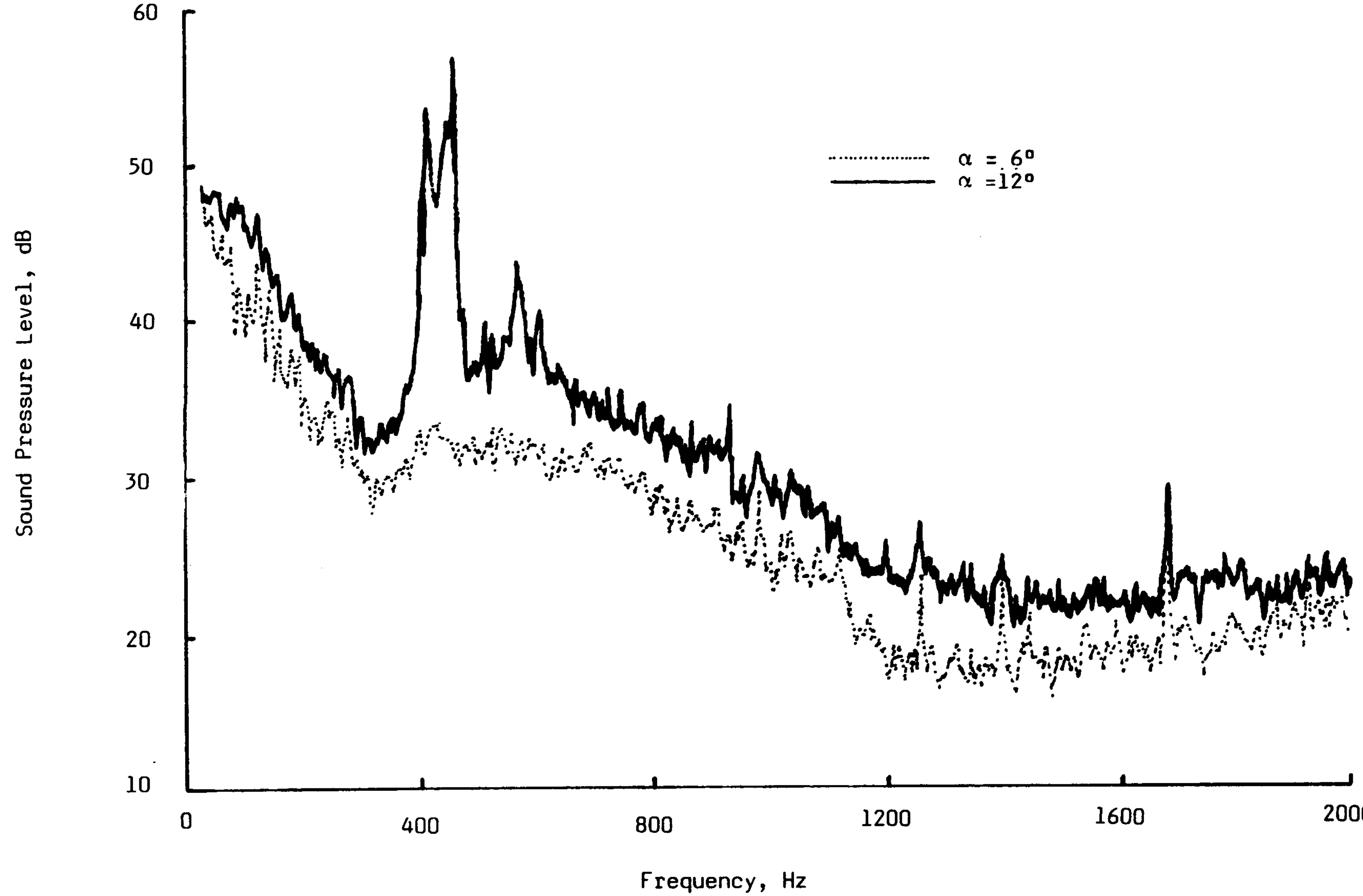


Figure 10. Narrow band (Δf=2.5 Hz) noise spectra upwind of the MOD-0/5A rotor with plain aileron for two deflection angles. r=57 m, V=4.0-6.7 m/s, P=20-22 kW.

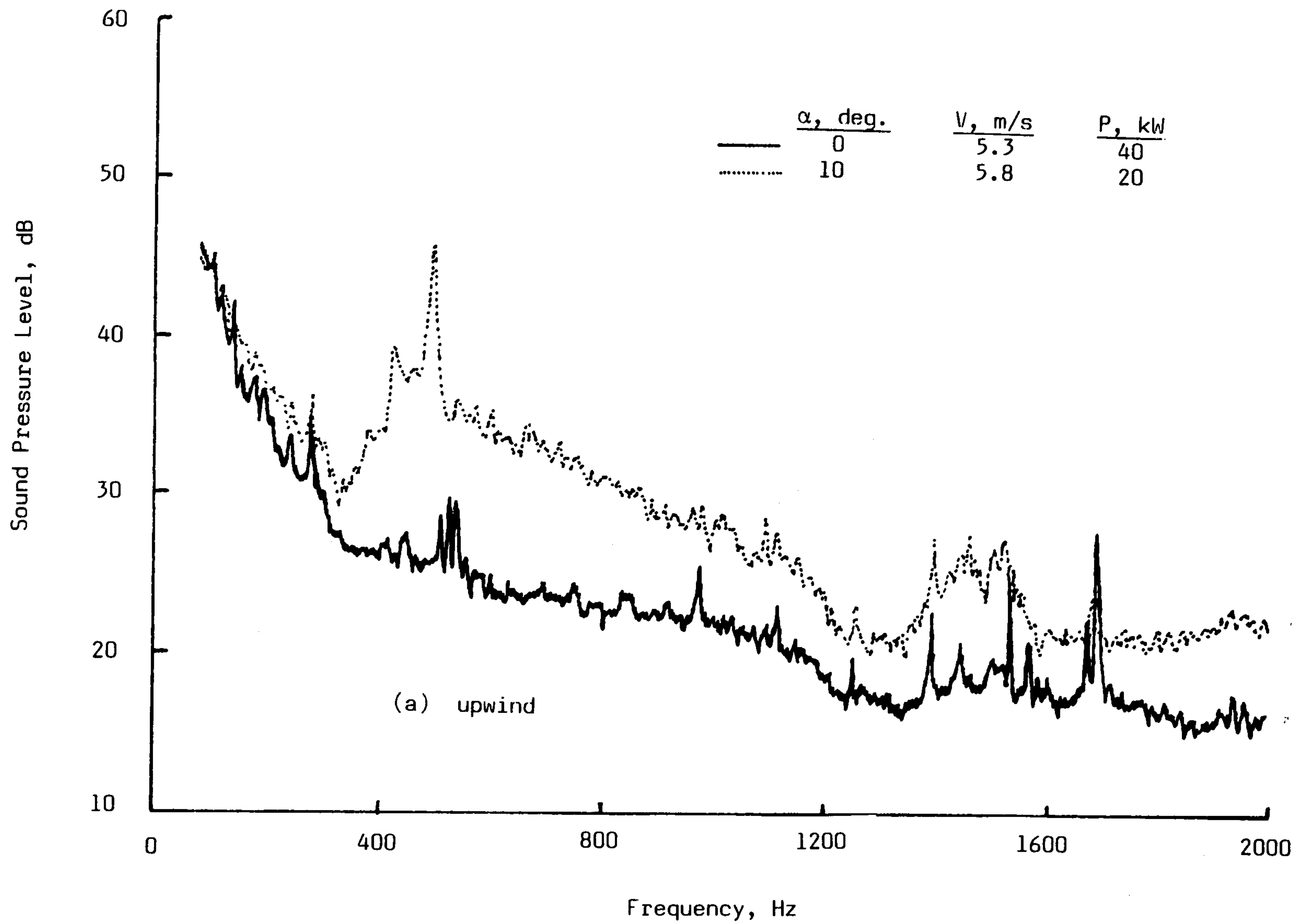


Figure 11. Narrow band (Δf=2.5 Hz) noise spectra of the MOD-0/5A rotor with plain aileron for two deflection angles. r=57 m.

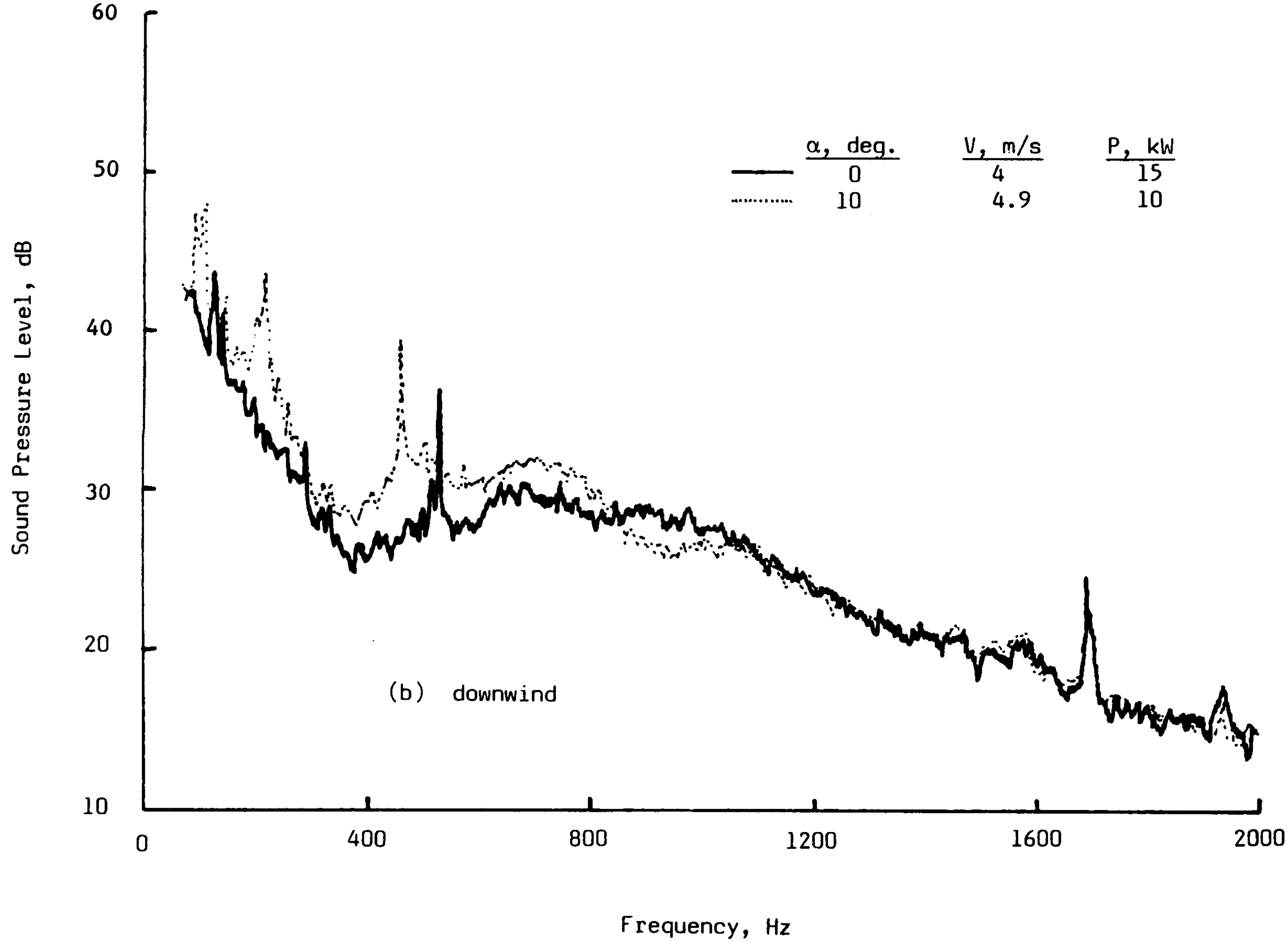


Figure 11. (Cont.)

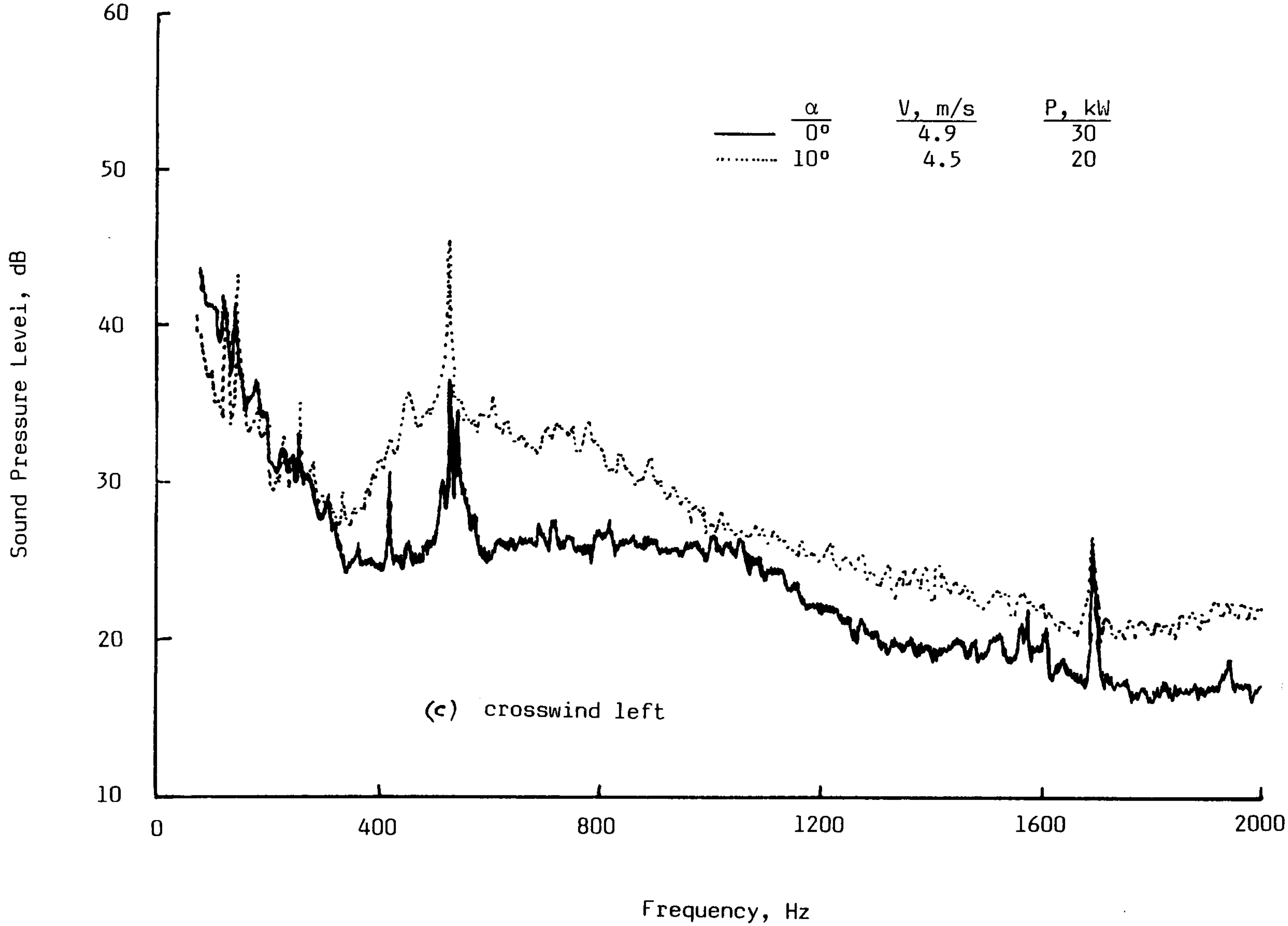


Figure 11. - (Concl.)

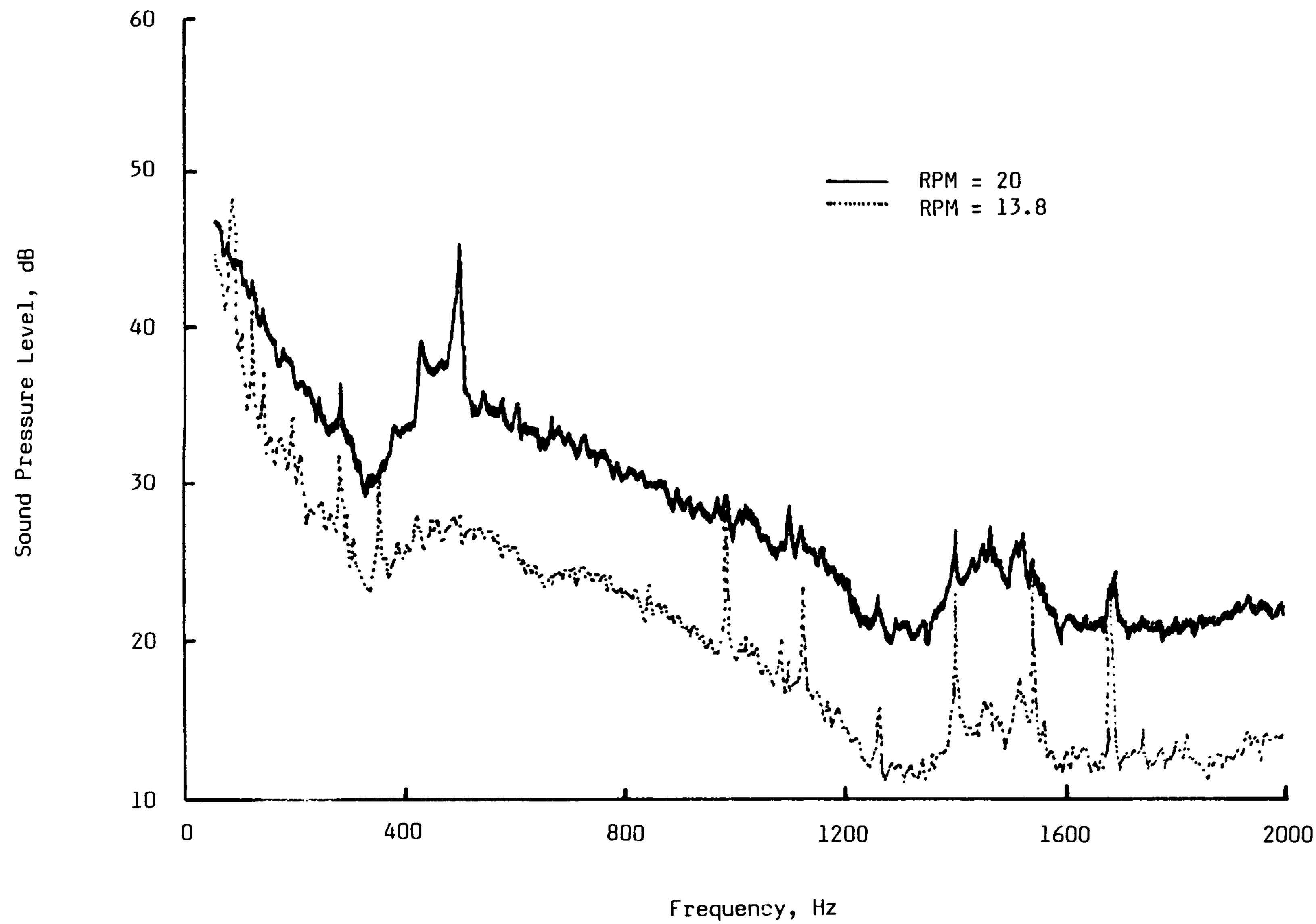


Figure 12. Effects of rpm on the upwind narrow band (Δf=2.5 Hz) spectra of the noise from the MOD-0/5A rotor with plain aileron. r=57 m, α=10°, V=5.8 m/s, P=21 kW.

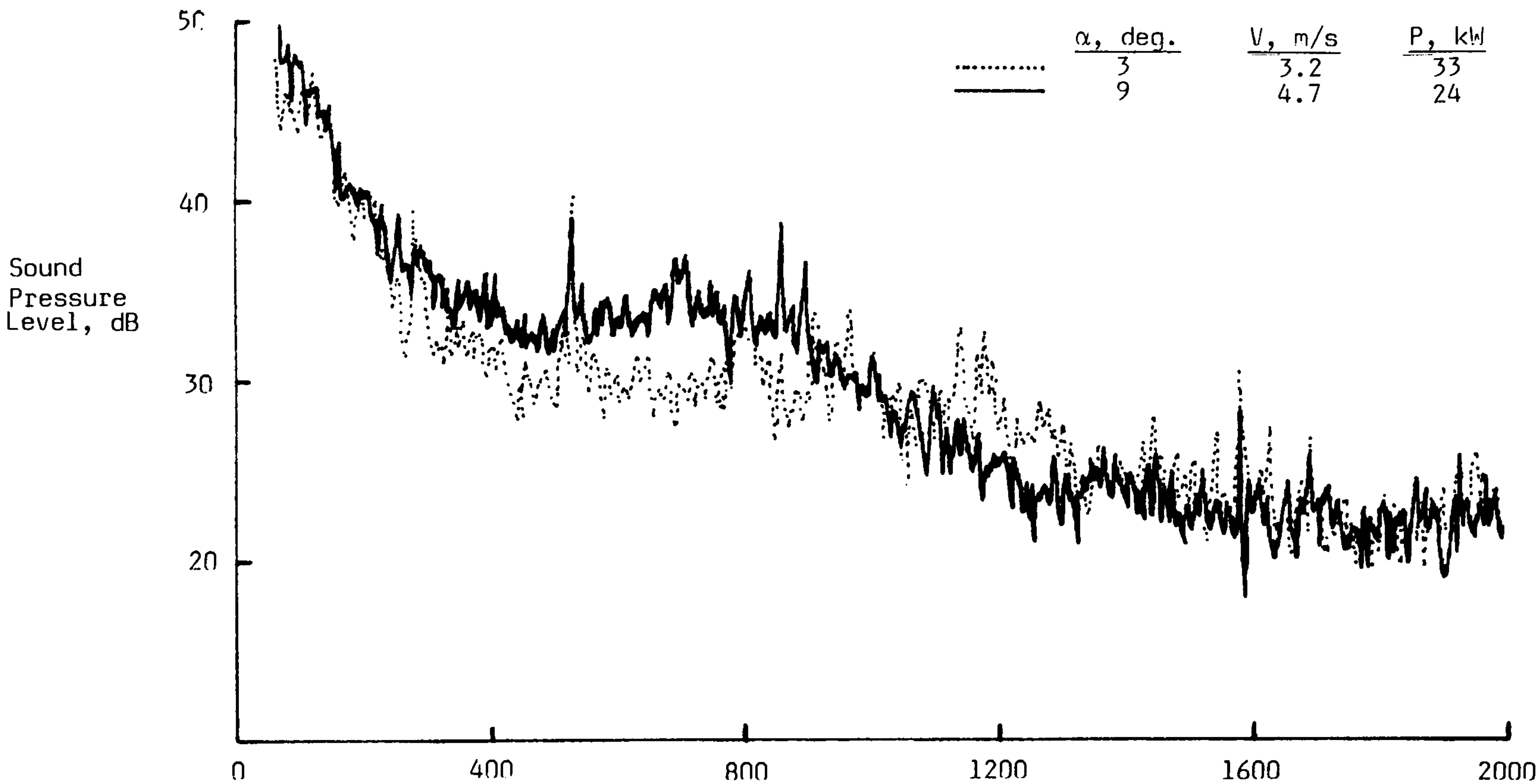
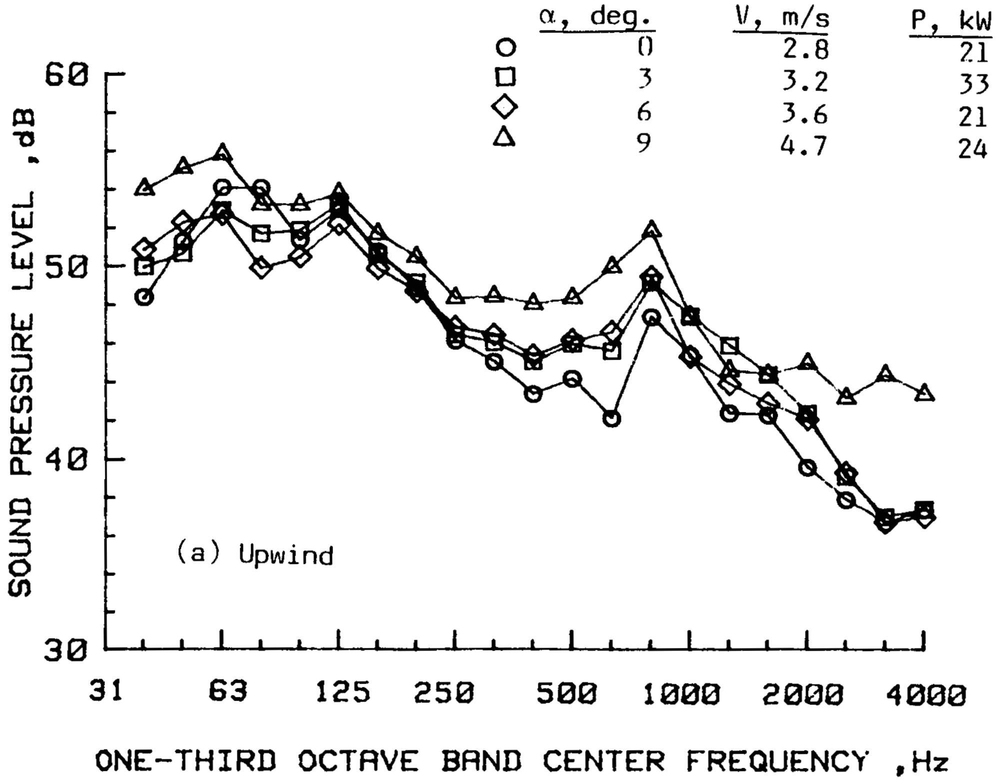


Figure 13. Narrow band noise spectra upwind of the MOD-0/5A rotor with balanced aileron for two deflection angles. r=57 m.



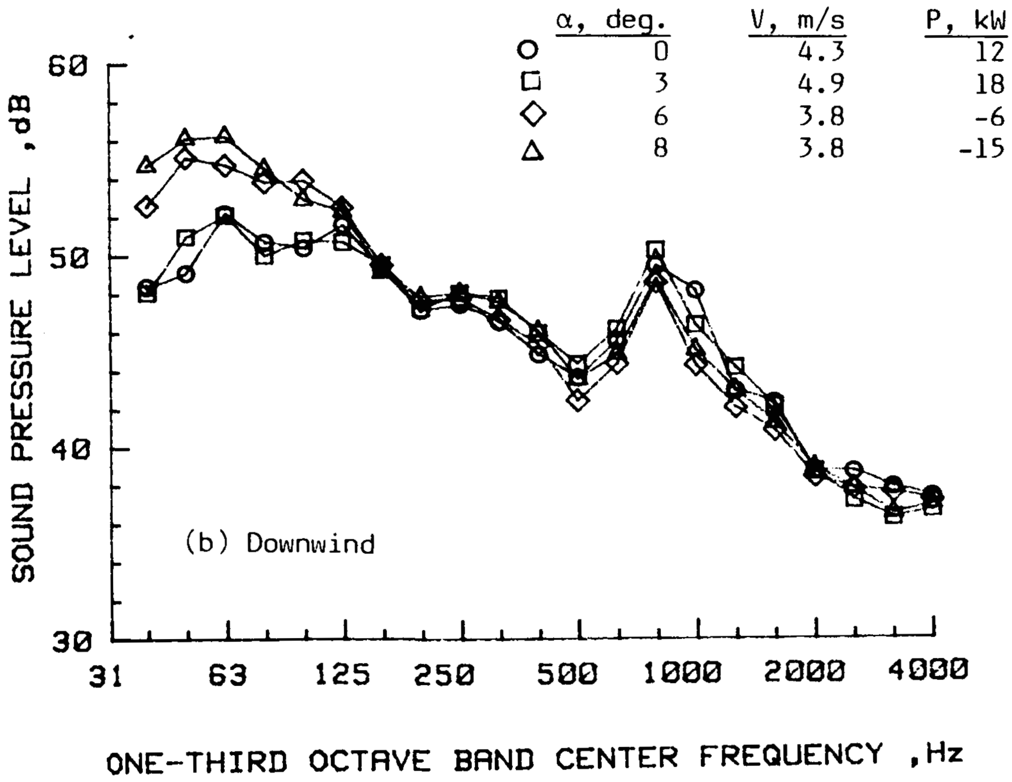


Figure 14. On-axis noise measurements for the MOD-0/5A rotor with balanced aileron over a range of aileron deflection angles. r=57 m.

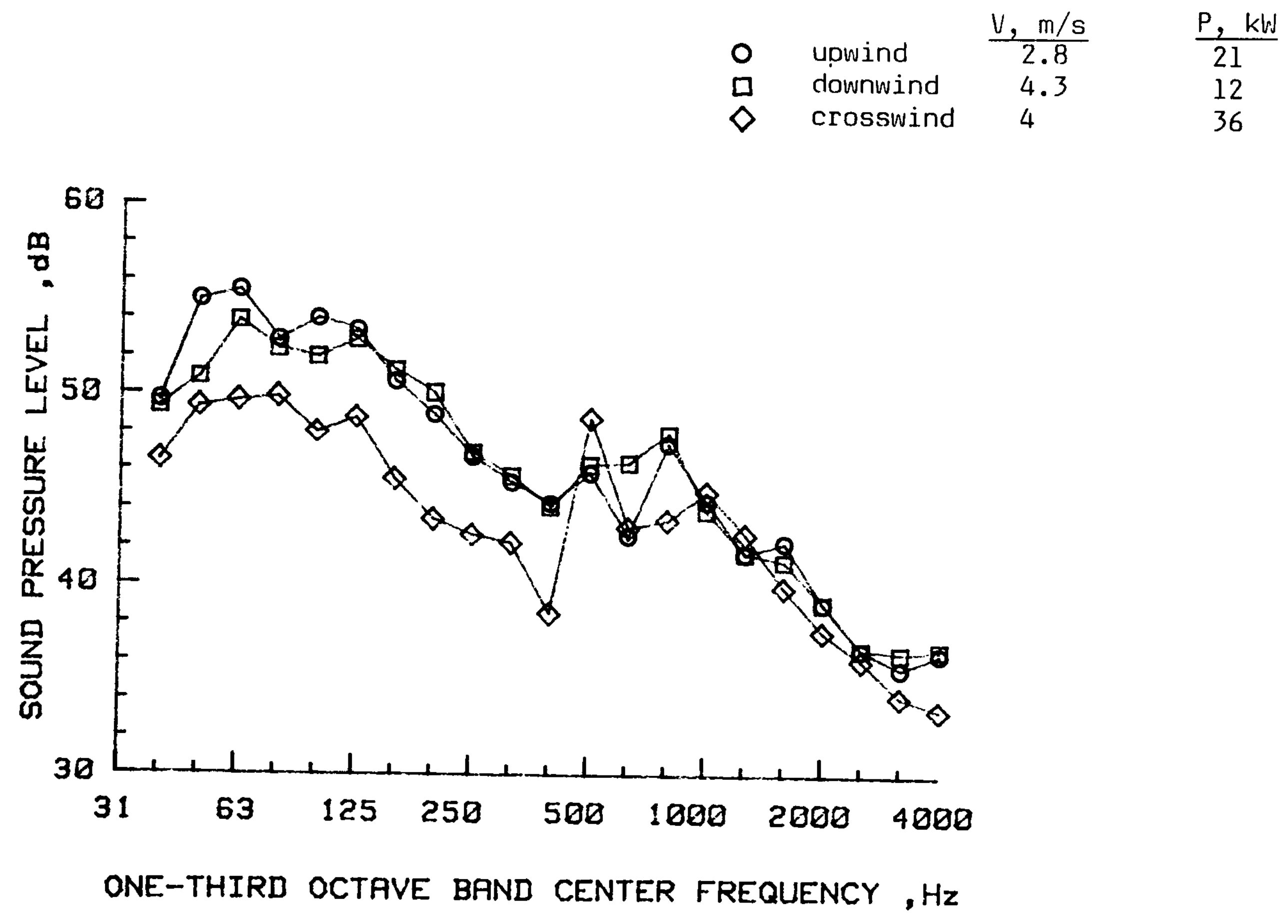


Figure 15. One-third octave band spectra of the noise from the MODO/5A rotor with balanced aileron in three different directions. $r=57$ m, $\alpha=0°$.

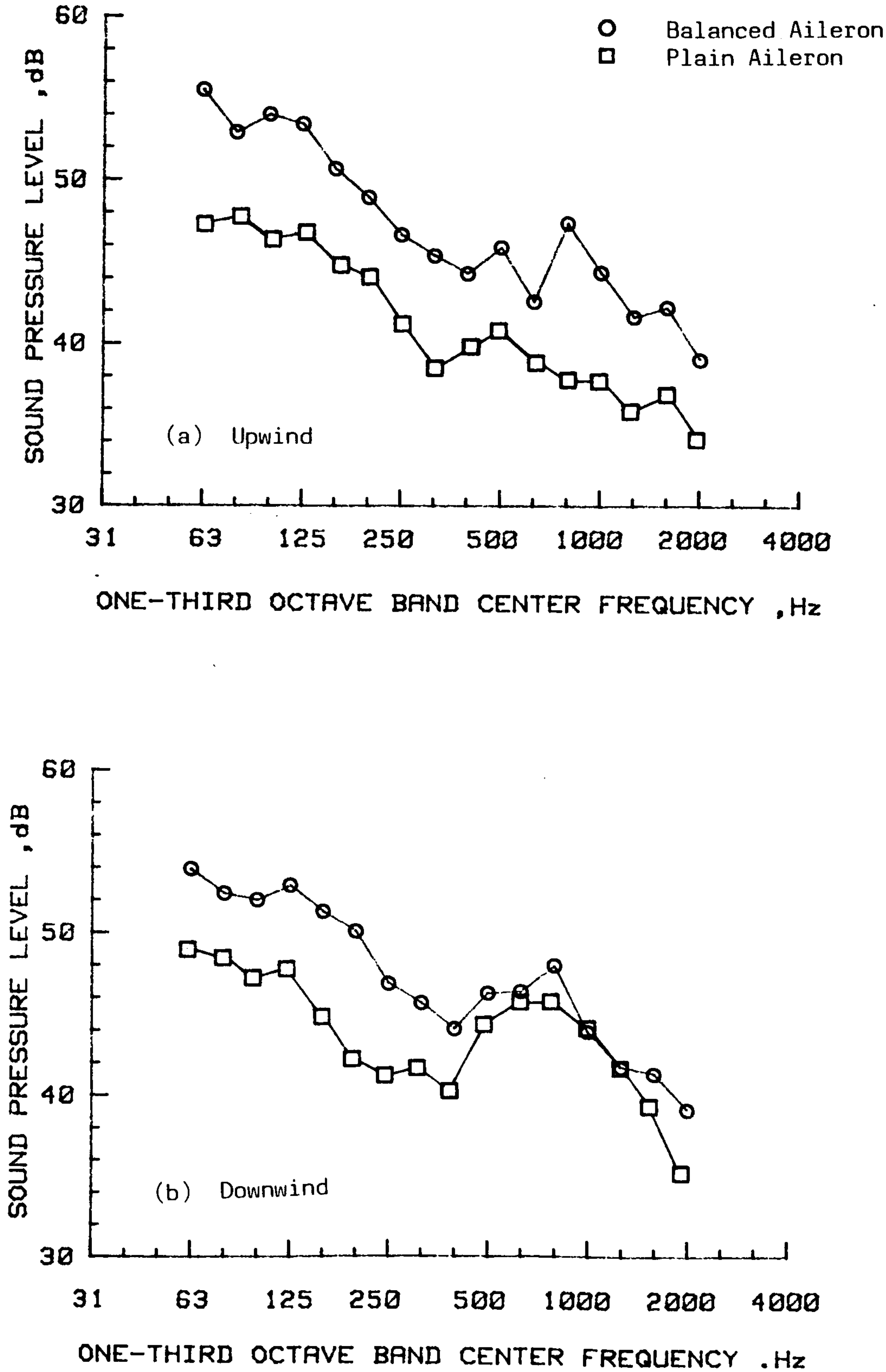


Figure 16. Comparisons of on-axis noise measurements for the MOD-0/5A rotor with plain and balanced ailerons. $\alpha=0°$, V=4-4.5 m/s, P=9-15 kW, r=57 m.

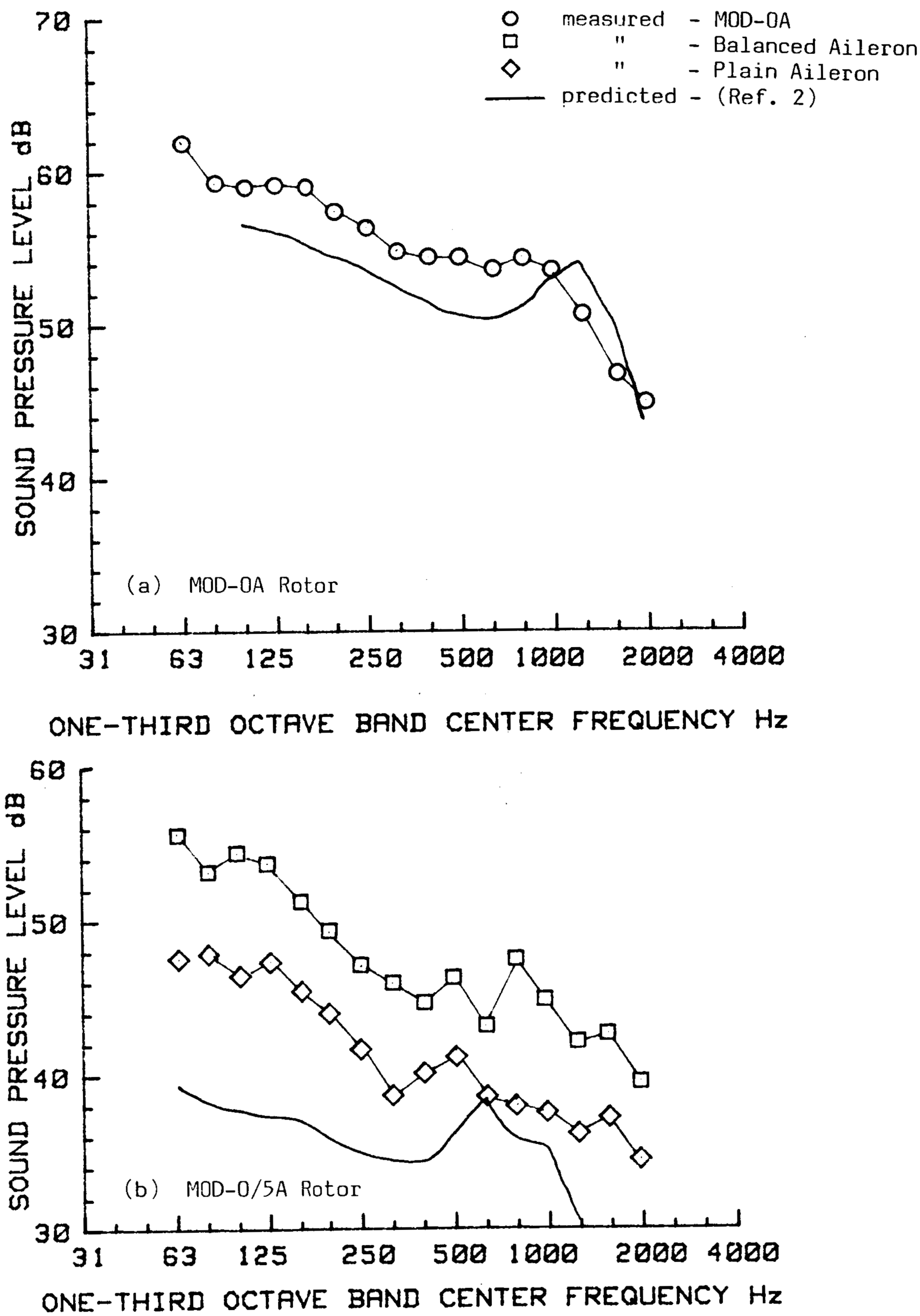


Figure 17 . Comparisons of measured and predicted one-third octave band spectra for the MOD-0A and MOD-0/5A rotors

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15. Supplementary Notes

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16. Abstract

Measurements of noise have been made for a MOD-0 wind turbine generator rotor equipped with plain and balanced partial span ailerons for lift and drag control. Data were obtained for a wide range of aileron deflection angles and for limited ranges of wind velocity and power output. Noise levels increased as deflection angles increased and were higher in the upwind than in the downwind direction. The plain aileron exhibited a howling noise in the frequency range 400-800 Hz at deflection angles for which flow induced cavity resonances were significant.

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