THE DANISH LARGE WIND TURBINE PROGRAM

B. Maribo Pederson
Technical University of Dermark
Lynby, Denmark

SUMMARY

A short account of the Danish wind energy program and its present status is given. Results and experiences from tests on the Gedser windmill (200 kW) are presented. The key results are presented from the preliminary design study and detailed design of two new WECS (630 kW each). These two new WECS are planned to go into operation in mid-1979. The Tvind project (2 MW) is briefly mentioned.

INTRODUCTION

The Danish Wind Energy Program was initiated 1977 and covers a four year period, up to January 1981. The total budget amounts to 41.4 Md.kr. or approximately $8M. Of this amount, 36.4 Md.kr. is used for development of large turbines. The different tasks of the program and their costs are delineated in table I.

The objective of the Danish program can be briefly stated as:

- Get fundamental answers on the feasibility of wind power in a utility grid. Hence, use demonstration units, not merely a test facility.

- Get better ideas of costs. That means building the demonstration units large enough so that reliable extrapolations to large sizes can be made.

- Get better ideas of reliability, maintenance costs and expected lifetime. Therefore, use two units of approximately similar design.

- Get answers fairly quickly.

TESTS OF THE GEDSER WINDMILL

The Gedser windmill, designed and built in 1956-57, was refurbished and operated from November 1977 to April 1979. The main characteristics of the windmill are stated in table II, and the general appearance can be seen from figure 1. Meteorological data were obtained from an instrumented mast situated 25 m to the west of the windmill.

The tests performed were intended to:

- Give information on the dynamic behavior of a stiff, three-bladed rotor
- Determine the power curve for this stall-regulated machine.
- Give information on the power quality obtainable with an induction generator.
- Gain experience in measuring techniques.

Since the tests have just ended, it is possible to give only some preliminary results. A full report of the tests will be ready in the fall of this year.

A sample power curve obtained from the 10 minute averages of wind speed and electric power output is shown in figure 2. Two-minute averages were used to produce the power curve on figure 3. In both figures, the calculated shaft power curves had no allowances for mechanical and electric efficiencies. Unfortunately, no high wind results were obtained. The maximum wind speed during test runs was approximately 18 m/sec. This means that the full effects of the stall-regulation have not been verified.

Figure 4 shows sample recordings of wind speed and electric power to indicate the magnitude of the fluctuations in electric output and also the influence of the averaging time used on the plotted results. A sample power spectrum is shown in figure 5.

The coupling to the grid during start-up presented no problems. Typically, the transient at the nearest transformer point would have an amplitude of 1.5 volts.

Valuable experiences on measuring equipment were gained. In particular, the transmission of data from the rotating parts to the ground station (by a telemetry system) turned out to be not as straightforward as was originally thought. The tests were interrupted on several occasions due to mechanical failure of different parts.

THE NIBE 630 KW DEMONSTRATION WIND TURBINES

The main effort of the Danish Wind Energy Program has been the design and construction of two 630 kW wind turbines. The main characteristics are listed in table 3, and drawings of the two, Model A and Model B, are shown in figure 6.

The main design features resulted from a four-month preliminary design study. A final design study was then carried out, and specifications were sent to manufacturers in February of last year.

Parts were ordered in May, and construction work is progressing according to plans.

The windmills will be operational in the latter half of 1979. It was decided at an early stage that the windmills should be quite similar. The main differences are that one (windmill A) is to be stall-regulated and provided with a stayed hub, while the other (windmill B) is fully pitch-regulated and with cantilevered blades. In most other respects the two windmills are similar.

The blades are of a mixed steel and fiberglass design. The outer 12 m of all blades are build up with a wound D-spar in fiberglass, around which is placed an outer shell, which also comprises the trailing edge. The shell is also fiberglass/polyester. Details of the rotor blades are shown in figure 7. The inner 8 m of a blade has a steel spar as the load carrying member and outer shells of fiberglass/polyester. Figure 8 shows the design of the junction between the outer and inner blade.

The choice of airfoil section (which should be the same on the two designs, so that the same mold could be used for all blades) was mainly determined to satisfy the needs of the stall-regulated machine. That is to say, an airfoil section was sought that gives a power curve as close to the ideal one as possible. The blade shape and twist of course also have an influence on the power curve.

Early in the study, the planform was chosen to be trapezoidal, and solidity, twist and airfoil section were the remaining parameters. The final result of the investigations was that NACA 44-series airfoil sections were preferable, and twist should vary linearly between tip and root with a total twist of 11.7°. Figure 9 shows the spanwise variations of chord, thickness ratio and twist.

The generator size was chosen to be around 500 W/m^2 and an optimum tip speed of 70 m/s was found. For the stall-regulated machine it was found that four different pitch settings would be adequate. A starting position of 15°, a running position for wind speeds below 10 m/s of 1°, above 10 m/s of -4°, and a brake position of -20°.

Power and thrust curves for the final design are shown on figure 10 and 11. The calculated power coefficient versus inverse tip-speed ratio, i.e., wind speed over tip speed, is shown in figure 12. Constant power curves for different pitch settings and wind speeds are shown in figure 13. Also shown in figure 13 are the anticipated pitch-setting versus wind-speed variations for rotors A and B. Power duration curves are shown in figure 14. The annual output, not corrected for mechanical and electrical losses is calculated to be 1,820,000 kWh for windmill A and 1,890,000 kWh for windmill B. Expressed as mean power per m^2, the numbers are 166 W/m^2 for windmill A, and 172 W/m^2 for windmill B. These numbers are for a median wind speed at hub height of 8.0 m/s.

The natural frequencies for a Model B blade have been calculated and are shown in dependence of rotational speed on figure 15. Paragon Pacific Inc., under contract for the Danish program, performed a structural dynamic analysis of Model B using the MOSTAS code. A sample calculation result (fixed shaft MOSTAB analysis) is shown in figure 16.

The tower is designed as a reinforced concrete conical structure (fig. 17). The two lowest natural frequencies have been calculated as 1.38 Hz and 7.34 Hz, respectively. Measured in the scale of the rotational frequency of the rotor, the numbers are 2.4 p and 12.8 p. This means that during start-up, one passes through resonance with the 3 p excitation.

The nacelle layout, i.e., mainshaft, bearings, gearbox, brake, etc., is conventional as can be seen in figure 18. The yaw drive mechanism is hydraulically operated, and so is the pitch regulation system. Four yaw brakes are provided.

The costs of each of the two machines are very much the same. Table IV shows how the costs are distributed for the different parts. The estimated costs for the following units are not to be taken as the price for a series production machine, but only as an estimate for a limited production for a design which does not differ from the present one. Also it must be mentioned that no attempt was made in the present studies to find an optimum size wind turbine.

THE TVIND MACHINE

The Tvind windmill project is a private enterprise which was undertaken by a group of schools in Denmark. Technical specifications are listed in table V. The windmill went into operation on March 26, 1978, and trial runs are still being carried out.

The windmill is operating at variable rotor speed, and that part of the electric power which is fed into the utility grid (425 kW) has to pass through a rectifier-converter unit to get the frequency right. The surplus power is fed through a resistor bank and used for heating purposes. The heat reservoir with heating coils has not yet been installed, and accordingly the mill so far has only run partially loaded. The heating system is expected to be operational in April 1979.

The system and design as such, up till now has shown no major deficiencies. A lot of smaller defects, however, have had to be corrected during the trial runs. During initial runs, readings were taken of the axial accelerations of the nacelle. Even when the rotor was passing through the speed where resonance with the first natural frequency of the tower (and the blades) was experienced, the measured accelerations did not exceed 0.2 m/sec^2.

One of the safety systems is blade-tip mounted parachutes, which are released when the centrifugal force exceeds a preset limit. The system has been tested and seemed to function satisfactorily. The automatic control system has not yet been operational, and all operations are done "by hand."

Noise emission, even when running at no load, is not negligible. In particular, the noise emitted when a blade passes the tower wake is quite noticeable.

DISCUSSION

Q. Has the Gedser machine been operated yet?

A. Yes, it has been operating but at a reduced power of 200 kilowatts of electricity.

Q. When do you expect to have the 630 kW machines in operation?

A. According to the plans, the first one will be up in the middle of June and the second one in September of this year.

Q. It appears in the photo of the Gedser wind turbine that the unit had acquired another set of cables since the earlier drawings of it. Is this an evolution aimed at restraining additional modes of bending of the blades?

A. Those cables were added ten years ago when it was running, and I am not quite sure why. What you are referring to might be the reason.

TABLE I. - DANISH WIND ENERGY PROGRAM, 1977 - 1981

	MdKr	
Tests on Gedser windmill	3.3	
Design and construction of two 630 kW WECS	20.4	
Siting studies	1.4	
Tests on two 630 kW WECS	6.0	
Theoretical studies a.o.	3.6	
Project management	1.7	
Subtotal, large WECS	36.4	($7 M)
Small WECS development, test station	5.0	
Grand total	41.4	($7.9M)

TABLE II. - MAIN CHARACTERISTICS OF THE GEDSER WINDMILL

Rotor location	Upwind
Rotor diameter	24 m
Number of blades	3
Blade tip velocity	38 m/s
Rotational velocity	30 rpm
Rotor area	450 m^2
Blade construction	Steel main spar, wooden webs, aluminum skin. Heavily stayed. Braking flaps in blade tips
Regulation	Stall regulated, no pitch control
Generator	Asyncroneous 200 kW, 750 rpm
Transmission	Double chain 1:25
Tower	Stiffened concrete cylinder Hub height, 24 m
Performance	Self starting at 5 m/s 200 kW at 15 m/s Typical annual production, 350,000 kWh/yr
Weight of one blade	1650 kg

TABLE III. - TECHNICAL SPECIFICATIONS FOR MOD A AND B

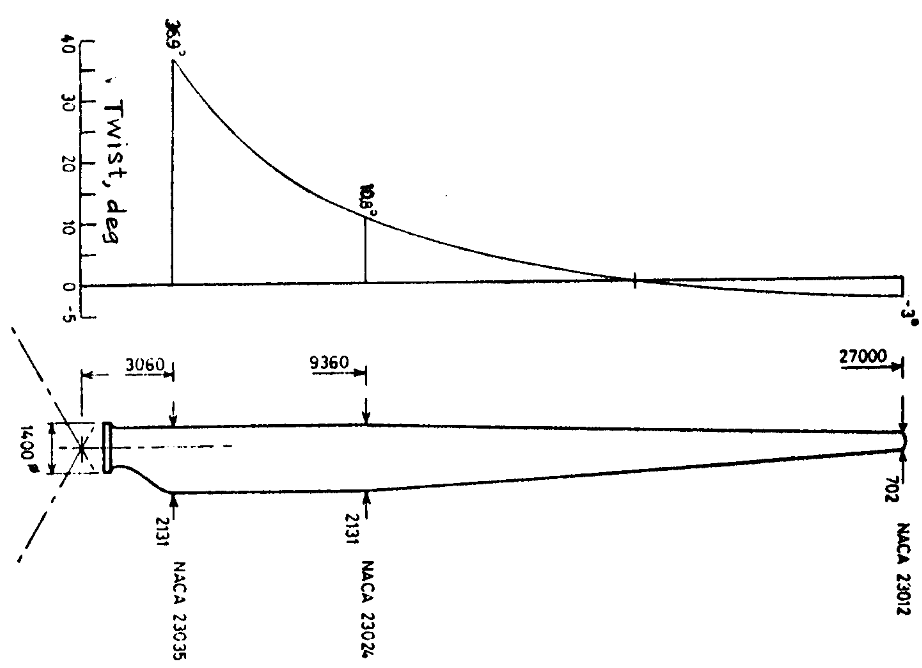
	MOD A	MOD B
Rotor diameter, meters	40	40
Hub height, meters	45	45
Tower height, meters	appr. 41	appr. 41
Rotor location	upwind	upwind
Number of blades	3	3
System life, yr.	25	25
Wind speed; cut-in, meters/sec	5	5
rated, -	appr. 13	13
cut-out, -	25	25
Weight of 1 blade, kg		3.370
Rotor speed, rad/sec	appr. 3.5	appr. 3.5
Rotor cone angle, deg	6	6
Rotor tilt angle, deg	6	6
Yaw rate, deg/sec	0.4	0.4
Pitch regulation:		
range, deg	+15 to -20	+90 to -1
maximum speed, deg/sec	6	8
normal speed, -	1	6
Generator: type	Asynch., 4-pole	Asynch., 4-pole
installed power	appr. 630 kVA	appr. 630 kVA
weight, kg	appr. 4000	appr. 4000
Transmission: type	conventional	conventional
ratio	appr. 1:45	appr. 1:45
weight, kg	appr. 10000	appr. 10000

TABLE IV. - PRICE BREAKDOWN, 630 KW WIND TURBINE

	Actual Price 1st Unit		Estimated Price Following Units	
	x 1000 d.Kr	%	x 1000 d.Kr	%
Acquisition of land and preparation of site	262	4	135	3
Electrical equipment and connection to mains	648	9	450	10
Tower	1,096	16	900	20
Nacelle, incl. rotor hub	2,822	40	2,000	44
Gearbox	260	4	250	5
Generator	135	2	125	3
Rotor, excl. hub	1,032	15	585	13
Assembly, running in	125	2	100	2
Consultants, rotor design	600	9	-	
	6,980 ($ 1.330 M)		4,545 ($.866 M)	

TABLE V. - MAIN CHARACTERISTICS OF THE TVIND WINDMILL

Rotor location	Downwind
Rotor diameter and area	54 m and 2290 m^2
Hub height	53 m
Number of blades	3
Max. rotational velocity	42 rpm
Blade construction	Fiberglass spar
Regulation	Pitch control
Generator	2 MW
Performance	Self-starting at appr. 5 m/s, 2 MW at appr. 14.8 m/s
Transmission	Conventional, ratio appr. 1:18.3
Tower	Reinforced concrete
Weight of one blade	5.2 kg
Weight of nacelle	100 kg



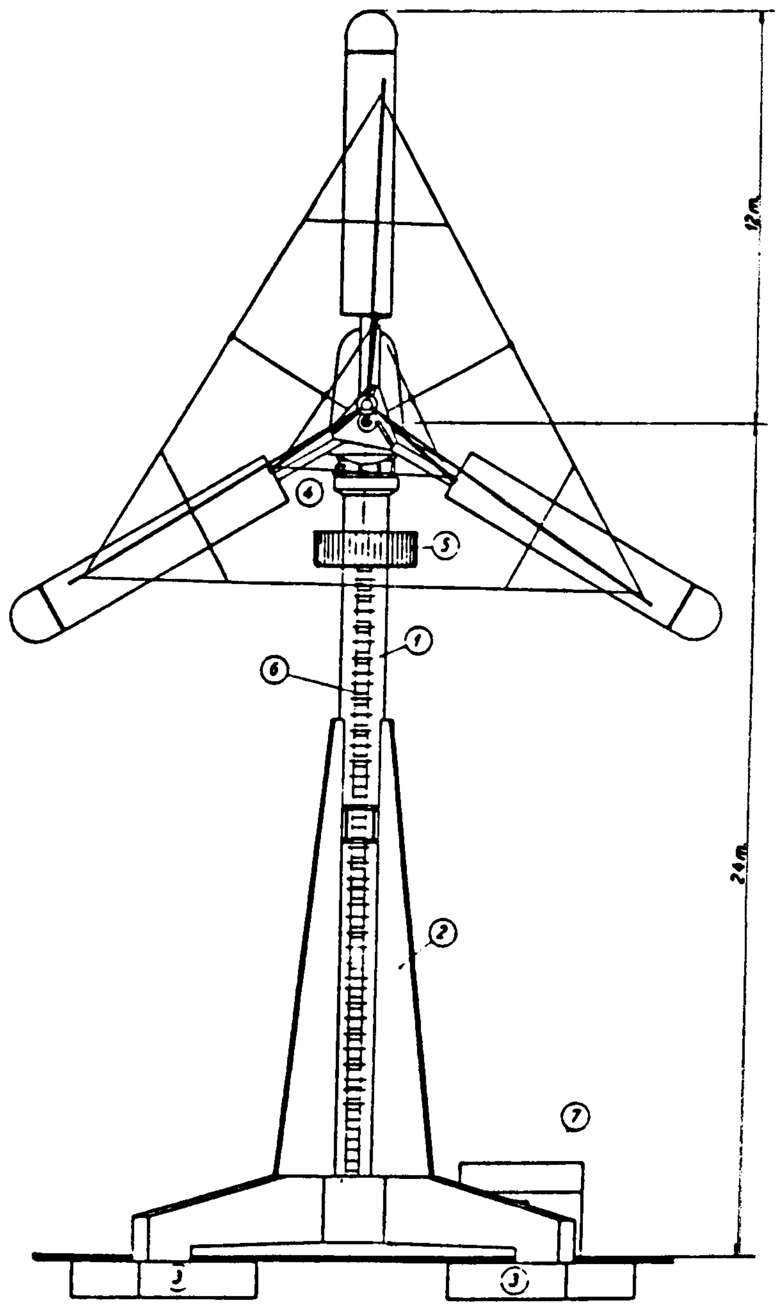


Figure 1. - The Gedser Windmill.

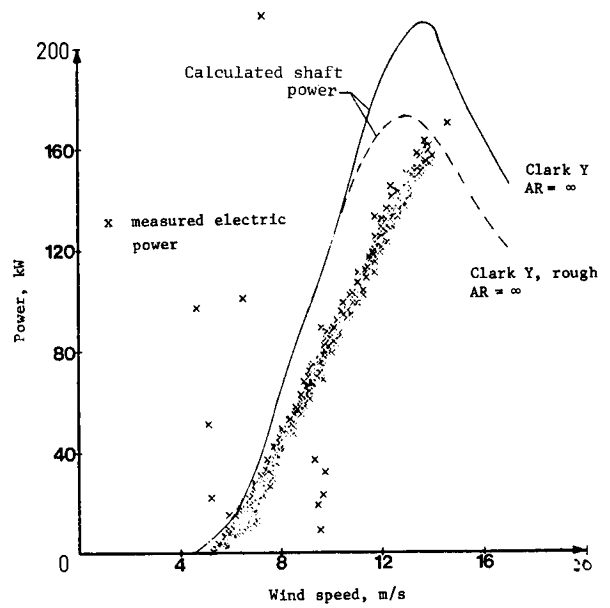


Figure 2. - A power curve for the Gedser Windmill. Block-averaged data for 10 minutes.

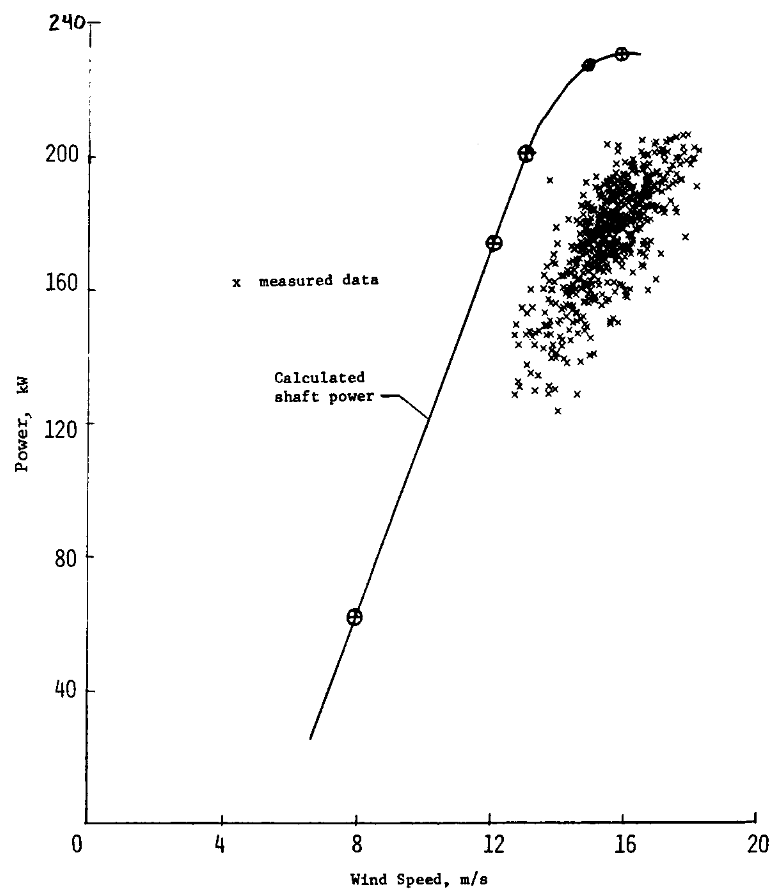


Figure 3. - Power curve for the Gedser Windmill. Data averaged for 2 minutes.

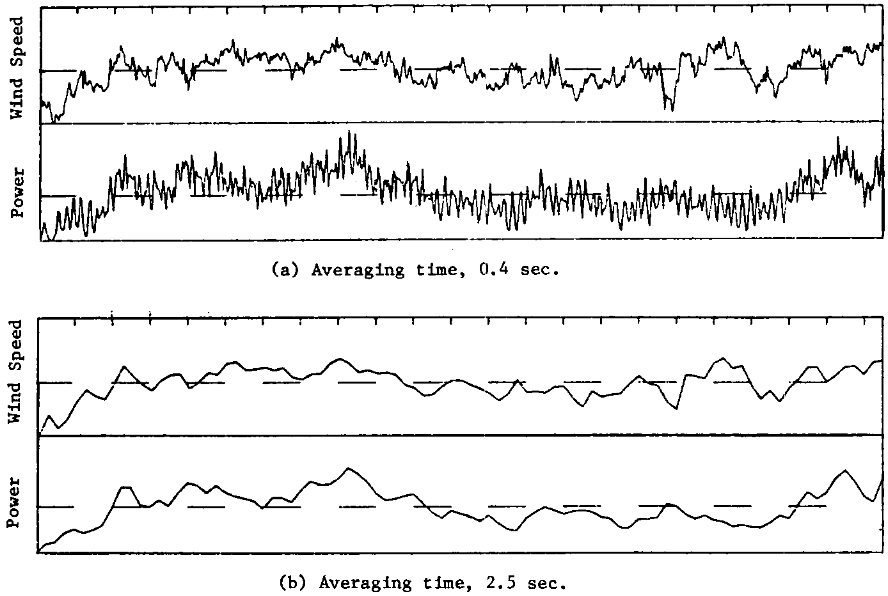


Figure 4. - Wind speed and electric power traces for Gedser Windmill showing power fluctuations and effects of averaging.

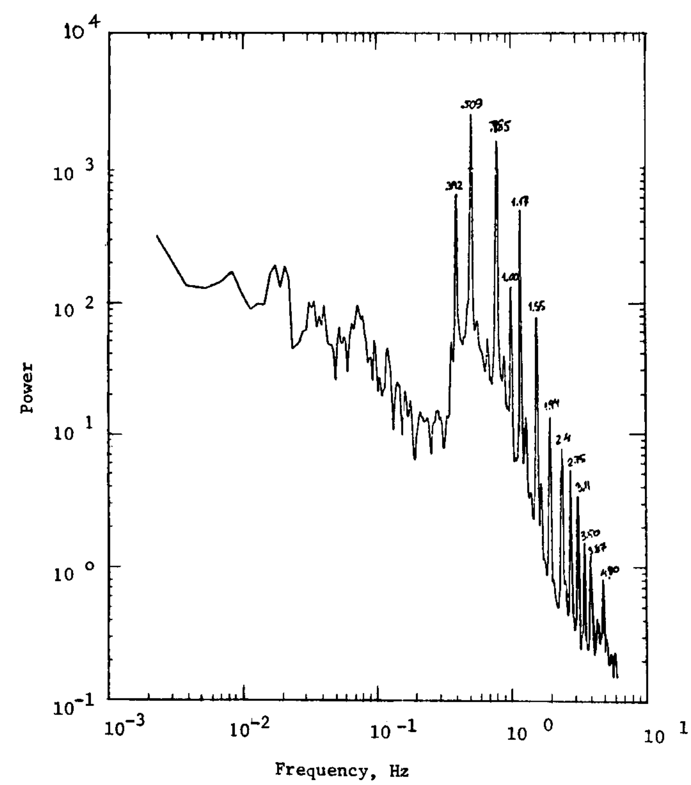
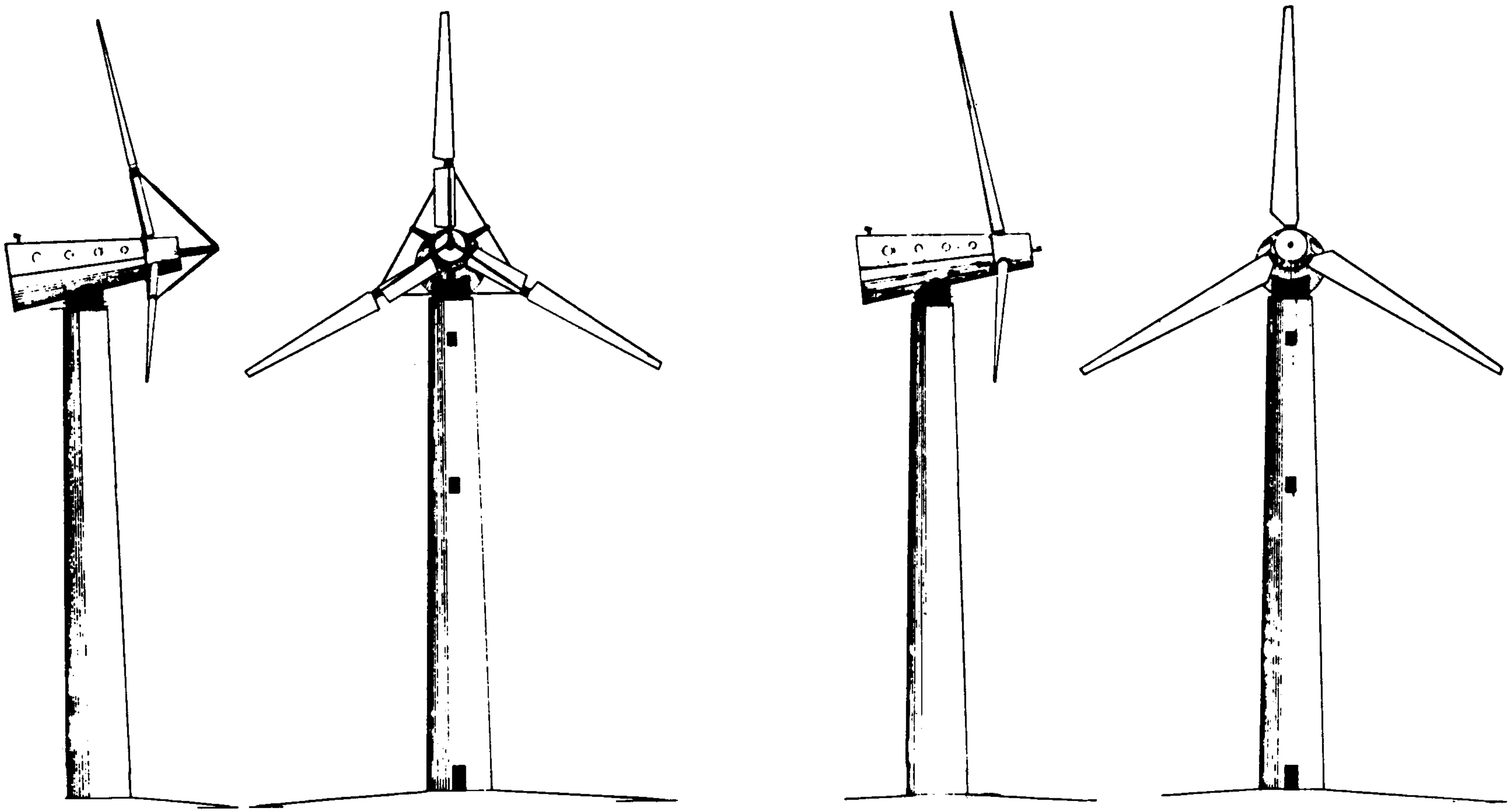


Figure 5. - Electric power for Gedser Windmill—power spectrum multiplied by frequency. Ordinate in arbitrary units.



(a) Model A (b) Model B

Figure 6. - Nibe 630-kW Demonstration Wind Turbines.

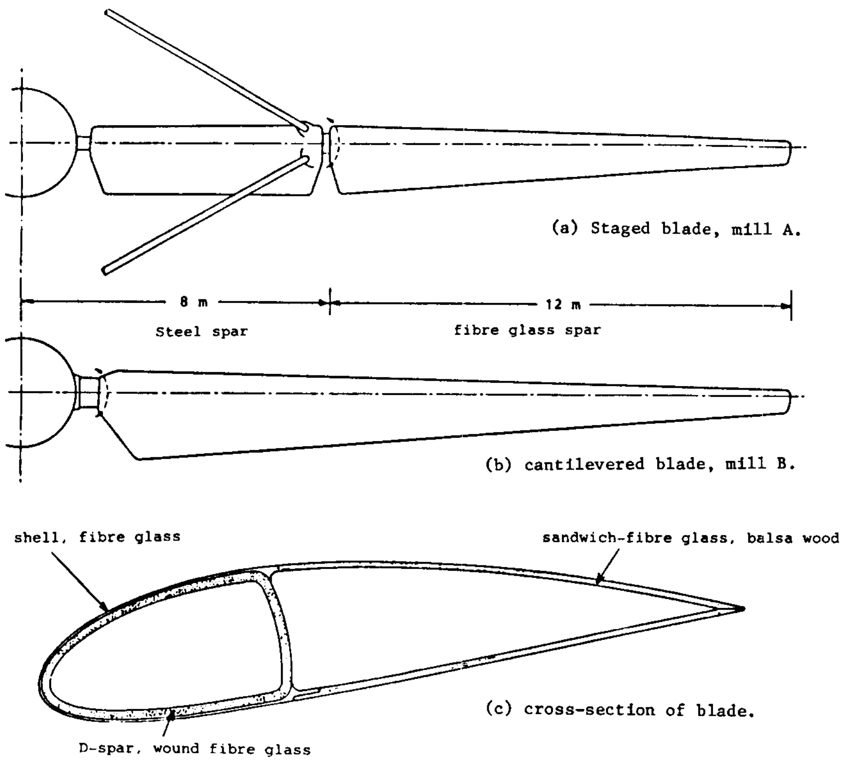


Figure 7. - Details of rotor blades. Nibe 630-kW Wind Turbines.

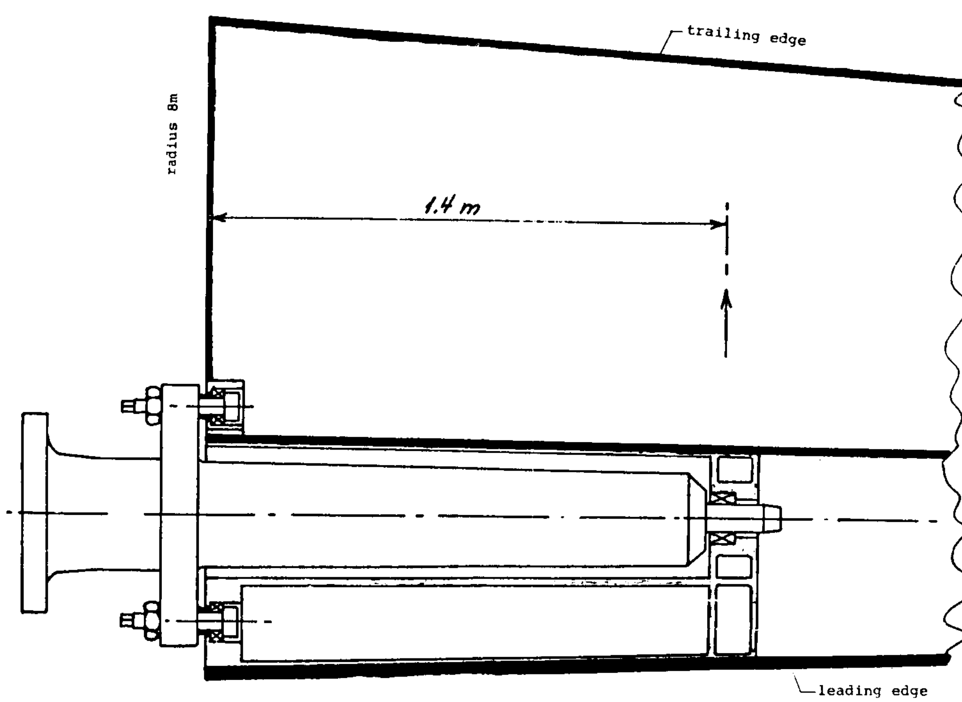


Figure 8. - Junction between outer and inner blade. Nibe 630-kW Wind Turbines.

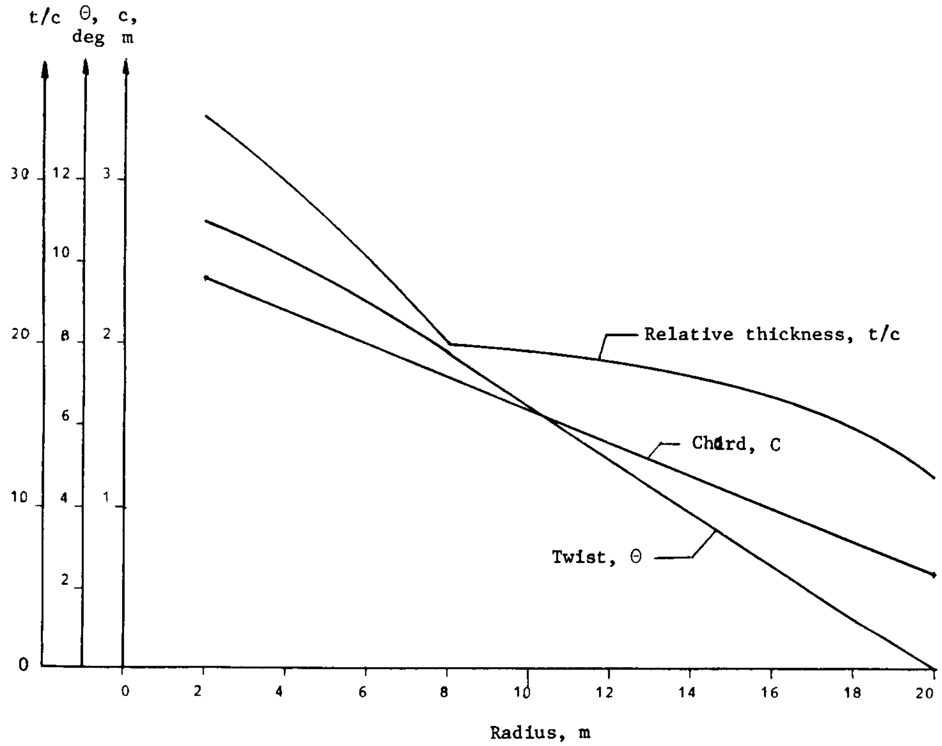


Figure 9. - Spanwise distributions for Rotor B, D = 40 m.

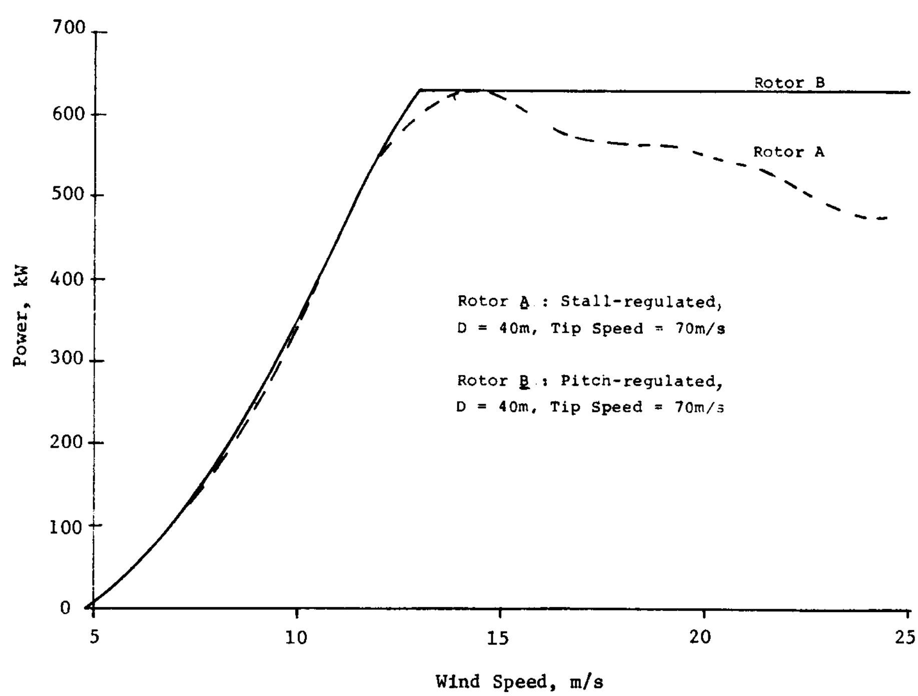


Figure 10. - Design power. Nibe 360-kW Wind Turbines.

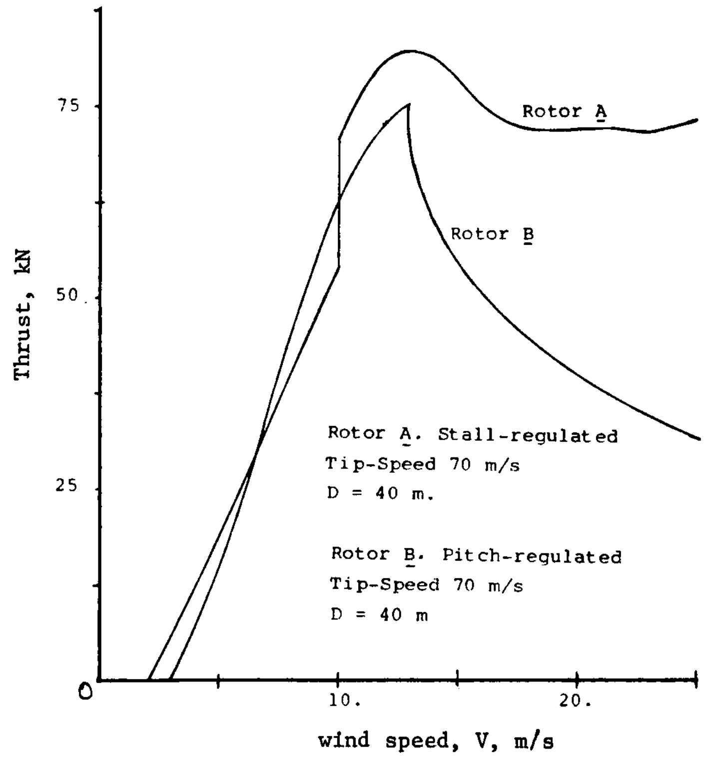


Figure 11. - Design thrust. Nibe 630-kW Wind Turbines.

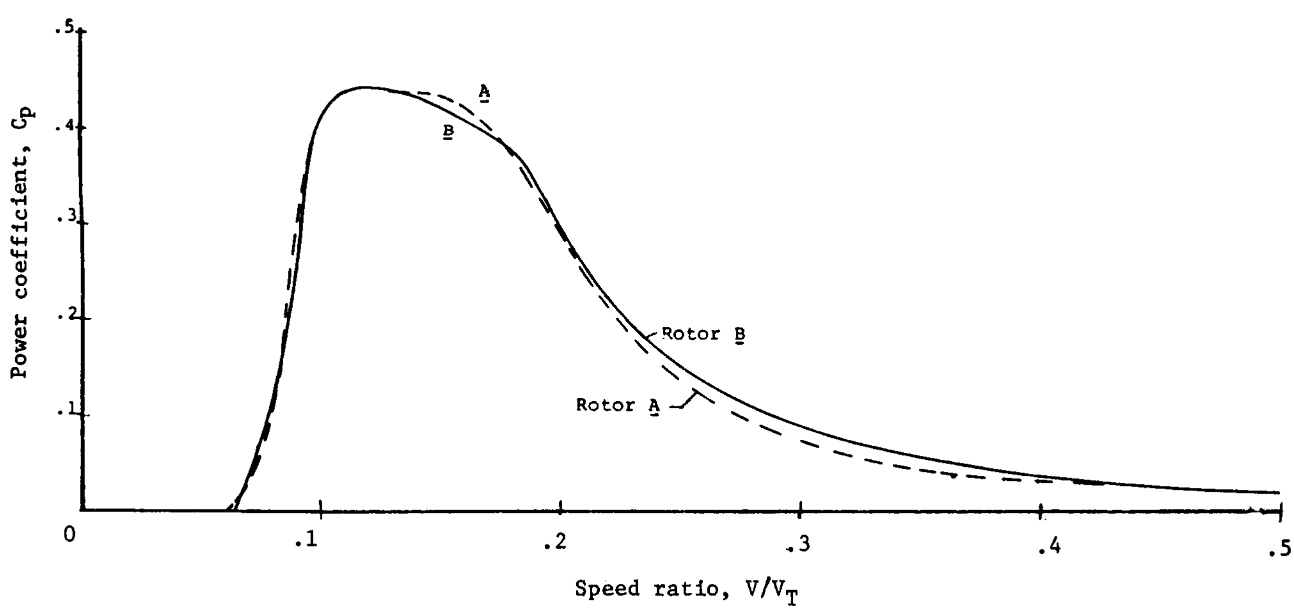


Figure 12. - Power coefficient curves. Nibe 630-kW Wind Turbines.

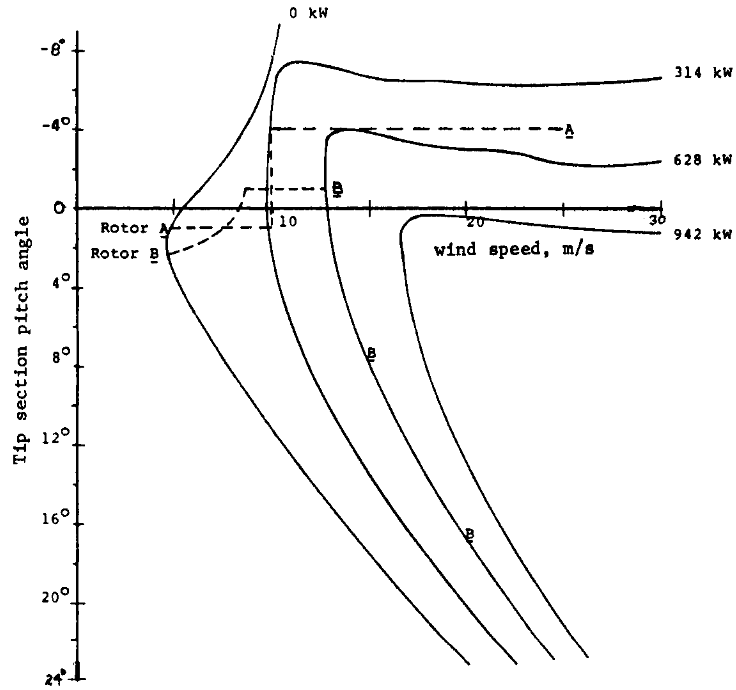


Figure 13. - Constant power curves with pitch regulation indicated.
Nibe 630-kW Wind Turbines.

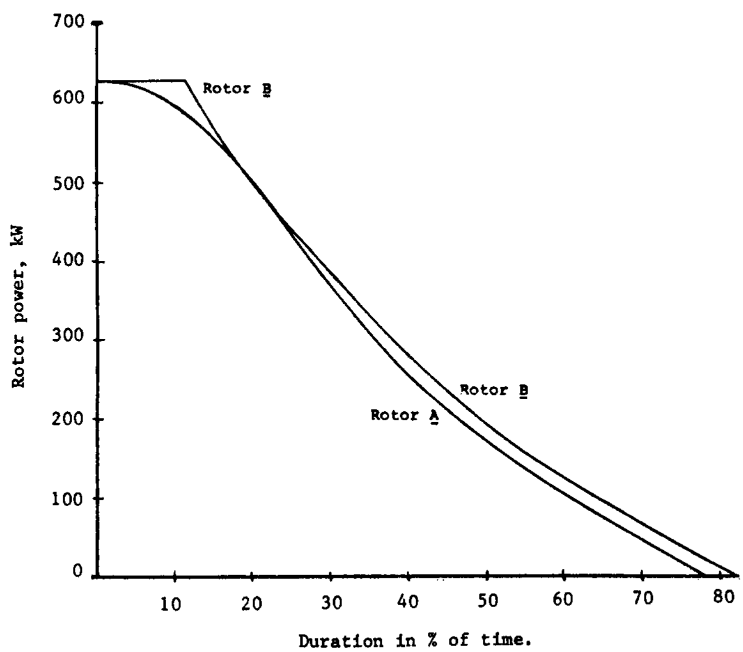


Figure 14. - Power duration curve. Nibe 630-kW Wind Turbines.

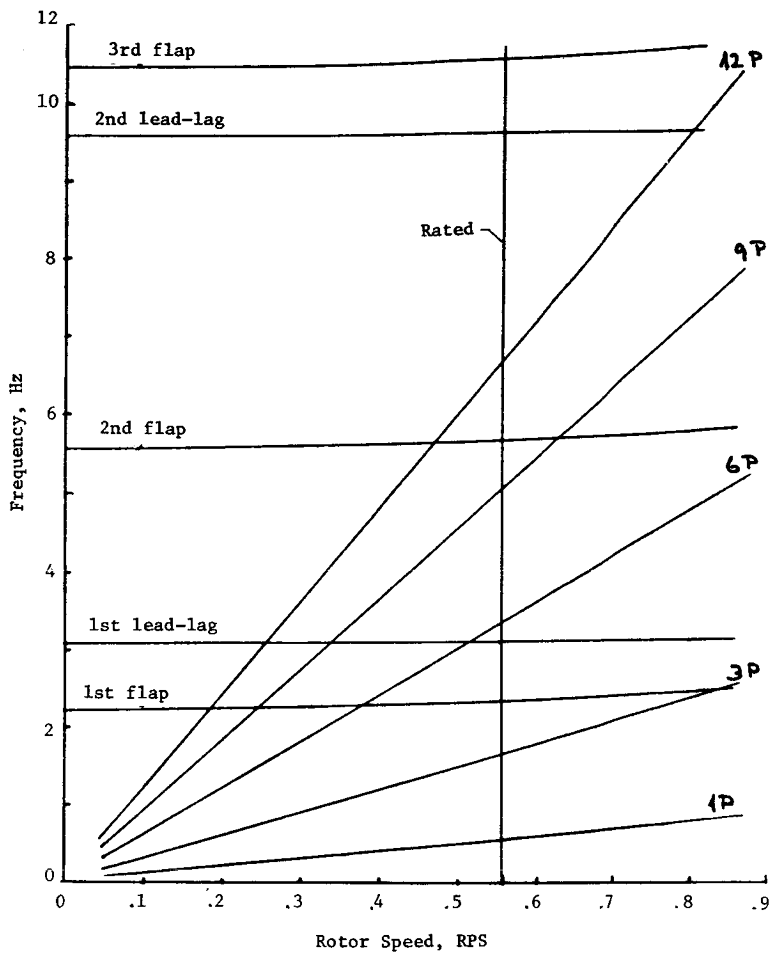


Figure 15. - Blade natural frequencies for Mod B blade. Blade mass, 3.365 kg.

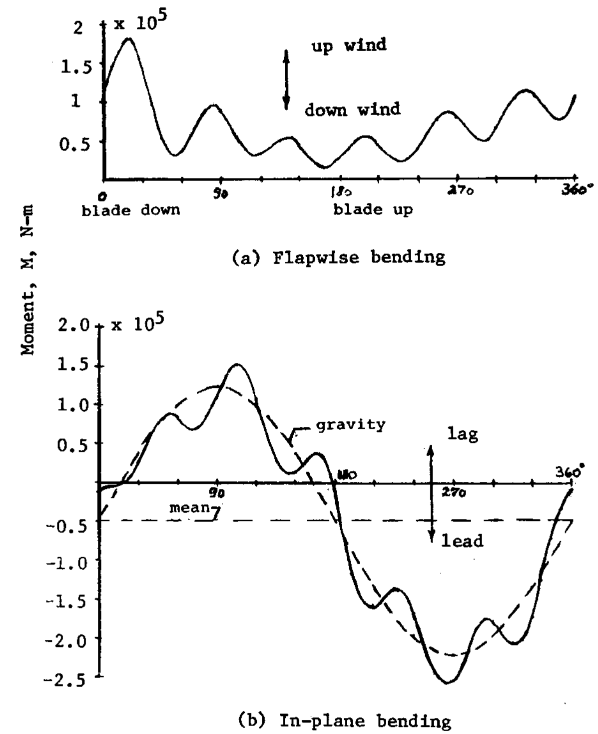


Figure 16. - Calculated blade root moments, Mod B. Conditions: $\Omega = 3.5\ s^{-1}$; $V = 22$ m/s; $\Theta_p = 20^\circ$; Yaw = 10°.

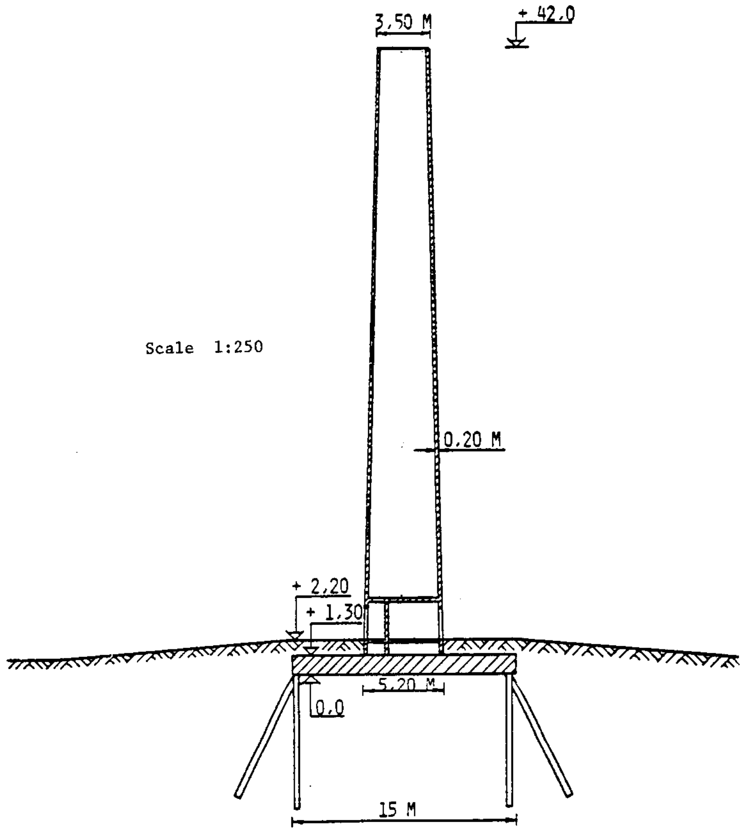


Figure 17. - Reinforced concrete tower. Nibes 360-kW Wind Turbines, Mod A and Mod B.

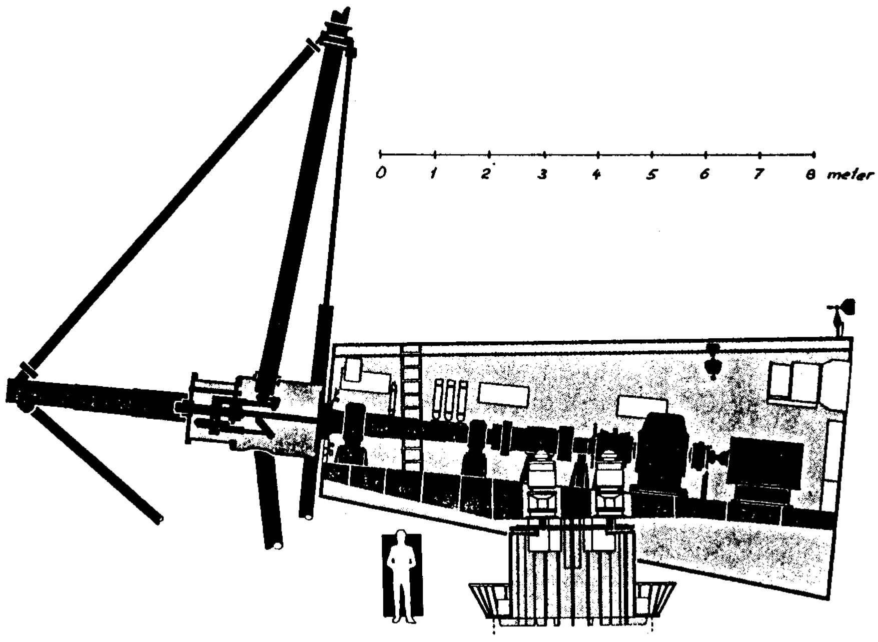


Figure 18. - Nacelle for Mod A. Nibe 630-kW Wind Turbine.