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COMPOSITE ROTOR BLADES FOR LARGE WIND ENERGY INSTALLATIONS

A. Kussman, J. P. Molly, and D. Muser

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16. Abstract The design of large wind power systems in Germany is reviewed with attention given to elaboration of the total wind energy system, aerodynamic design of the rotor blade, and wind loading effects. Particular consideration is given to the development of composite glass fiber/plastic or carbon fiber/plastic rotor blades for such installations.			
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Composite Rotor Blades for Large Wind Energy Installations

A. Kussman, J. P. Molly, and D. Muser

In 1976 the Federal Industry for Research and Technology /40* started planning a large scale wind energy installation (Growian), which was to determine the economic production of energy with direct supply to a public power supply network. The results of previous studies in our country and abroad led one to expect that the specific investment costs per installed kilowatt would be lower with increasing size, and therefore very large wind force installations would probably be most likely capable of having competitive electrical power generation costs.

Specifications of the Design Data.

The DFVLR was associated with the contractor firm MAN - New Technology in Munich in several projects. The Institute for Construction Research, directed the effort for the DFVLR. It collaborated in specifying the overall Growian system, participated in the aerodynamic design of the rotor blades, calculated the wind-induced and mass-induced loads on the rotor and made the final composite rotor blade designs.

2MW to 3MW electrical power levels at a wind speed of 12 meters per second was established as the basic input data for the design. This is measured at the level of the hub of the rotor. Based on the information from earlier wind electrical power generation stations, we decided to build a two blade rotor with horizontal axis. First it was necessary to specify the dimensions of Growian using rough estimates. For the power load on the rotor circular surface of 380 W/m^2 which was felt to be required, the rotor diameter was found to be 82 meters

*Numbers in margins indicate foreign pagination.

2 MW power level and 100 meters for a 3 MW power level, which had not been built anywhere else in the world before. An optimization calculation for the yearly energy for the planned erection sight resulted in a most favorable rotation rate of 18.5 rpm for the 100 meter rotor. The MAN company decided to pursue this design further. After this step, all of the boundary conditions for the accurate aerodynamic design of the rotor had been specified so that work could start at the Institute.

As far as the overall system is concerned we also have to say that the tower height was also optimized. The possible energy gain was considered when trading off the height above the ground (increasing wind speed, boundary layer near the ground) and the increasing tower costs. The optimum tower height of 100 m resulted, which means that Growian should produce about 2 of electrical energy every year.

As the version of Growian shown in Figure 1 shows, we selected a tube tower with stays, which required a rotor axis inclination of 10 degrees upward and a cone angle of 9° in order to provide enough clearance of the rotor from the stays, since it was desired to have the center of gravity near the tower. In addition, in the blade load calculations we had to consider possible rotation rate fluctuations of $\pm 15\%$ with respect to the nominal rotation rate, because we wanted to use an asynchronous generator made by the firm Siemens which has two power supplies. Within this fluctuation range it provides a constant three phase current of 50Hz. In the event of gusts, it is /41 permissible to have a dynamic evasion of the rotor by changing the rotation rate, which substantially contributes to the reduction of the instantaneous shocks.

Aerodynamic blade design

In preliminary studies we investigated various aerodynamic rotor blade designs for a rotor diameter of $D = 113$ m. From this

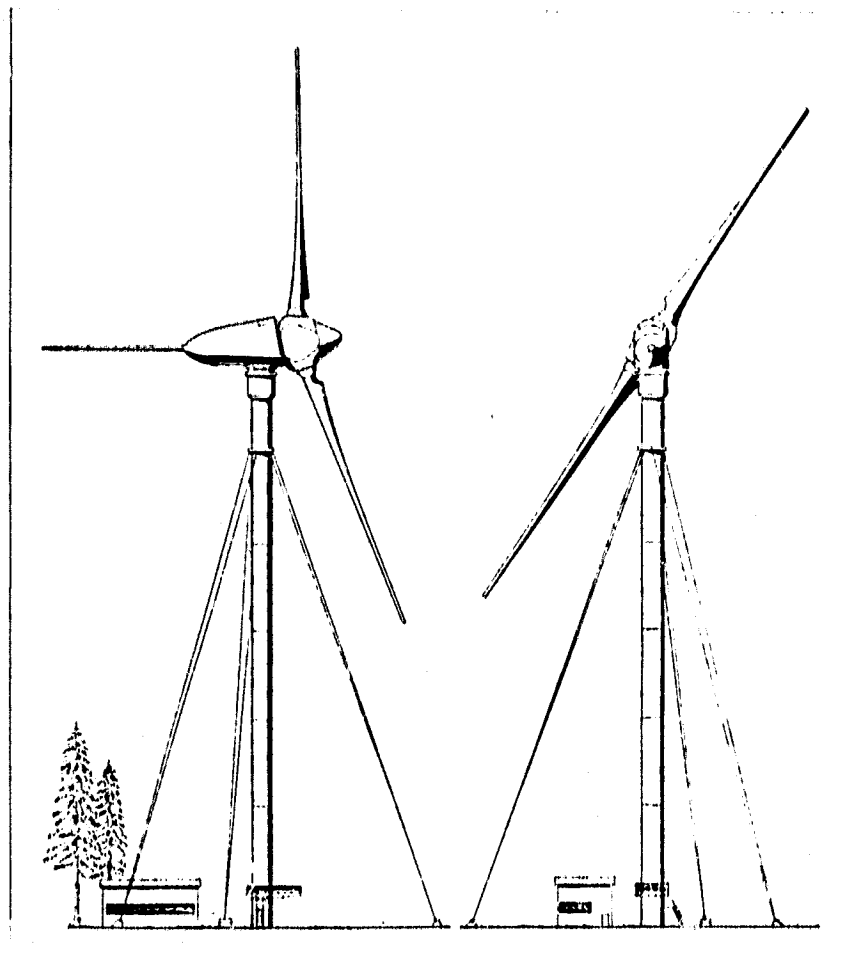


Figure 1. Growian overall installation.

We obtained optimal operating states for fast running coefficients of around $\lambda = 10$ at about 2-3 nominal power output for wind speeds of $v_0 = 10$ m/s. For the rotor blade design $R = 50.2$ m we therefore assumed the data determined, in order to achieve the maximum power coefficient $C_{p \max}$ of $\lambda = 10$.

Already in preliminary studies using several blade configurations of the 56 meter blade with symmetric NACA-00XX Series profiles and a linear thickness distribution of $d/t = 18\% \dots 10\%$, it was found to be necessary to increase the height of the profiles in the outer regions of the rotor blade. During the optimization of the 50 meter rotor blades, we first used a constant

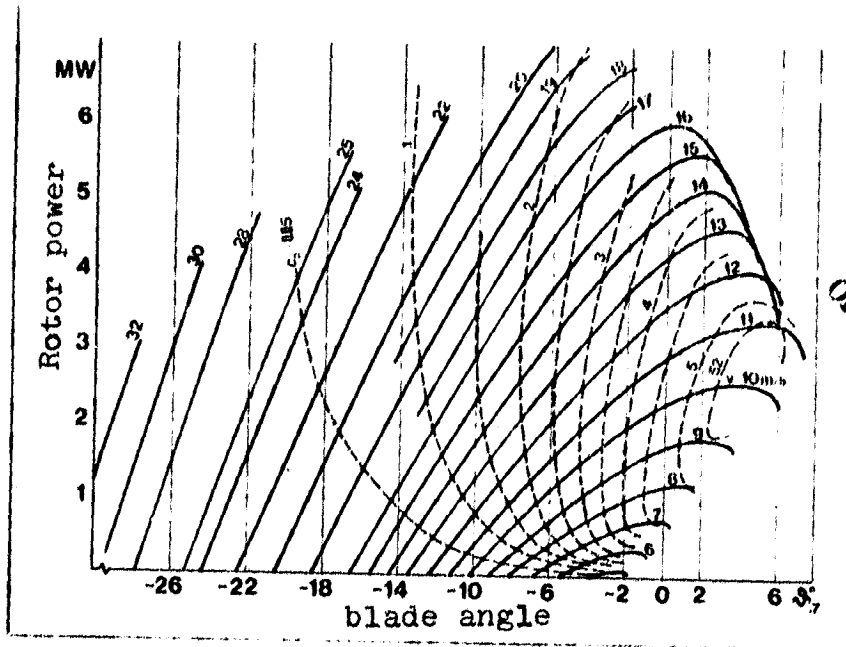


Figure 2. Performance characteristic field of the 100m rotor.

profile thickness of $d/l = 18\%$ and a slightly modified NACA profile 63₃618, the gliding coefficient of which was reduced in order to consider the increased roughness value of the blades (due to long time weather influences without cleaning the surfaces). As the final blade configuration we then had available the data of the special wind rotor profile series FX 77-W-XXX, which were generated by Professor Wortmann. The blade cross sections required for the loads led to a thickness distribution, which varies from $d/l = 15\%$ at the blade tip in a non-linear fashion up to about $d/l = 40\%$ at the blade beginning.

In the aerodynamic rotor blade design we have to make a compromise in the blade shape, between the simple form or easy manufacture and the aerodynamic quality of the rotor blade, that is, the conversion efficiency for energy conversion.

The determined theoretical blade outline (for a constant lift coefficient) has relatively straight contours in the outer half of the blade which is aerodynamically especially effective, and these contours have to be carefully maintained. A trapezoidal

blade cross section in the outer region comes closest to the aerodynamics requirements and overall is a favorable configuration, also with respect to strength requirements and manufacturing conditions. We first carried out a blade area optimization for a constant tip configuration, but its strength characteristics were not completely satisfactory. This finally led to the now adapted configuration of the rotor blade with a somewhat enlarged tip.

The design concept will have a lift coefficient distribution which decreases somewhat towards the blade tip for the wind speeds in the nominal power range ($v_0 = 12..25 \text{ m/s}$). In the partial performance range, in order to better exploit the low wind speed, the optimum operating points (c_{pmax}) will be achieved with approximately constant radial distribution of the lift coefficient C_a . From this, using the blade cross section we then find the twist variation of the rotor blade. Figure 2 shows the calculated performance characteristic field of the 100 meter rotor.

An additional task of the optimization process for rotor design was to investigate the influences of the blade cone angle and the blade angle feedback on the ground loads. Also it had to determine the load amplitudes and the flapping motion of the rotor in order to recognize both positive and negative coupling effects.

Wind-Dependent Load Assumptions.

The characteristic wind conditions near the ground produced several typical loads on a wind power generation station. First of all the effect on the rotor lead to substantial overall structural loads. During the investigations we soon found out that the available meteorological data were not sufficient for an exact description of the possible conditions. Unfortunately,

we do not have very many load measurements for wind power generation stations. Therefore the definition of the wind-load assumptions is only supported by very general and basic conditions.

The atmosphere motion has a boundary layer near the ground on a statistical average, which means an increase in the area average of wind speed from 7.0 m/s at 10 m to 9.3 m/s at 100 meter height above the ground for the coastal location we are planning to use. Analyzed over a long time the rotor therefore moves in a continuous ground boundary layer. Instantaneous differential loads between the top and the bottom blades however can have completely different radial distributions, and this is also true for gust processes.

The gusts were classified into frequency classes depending on their excess speed factors. It was assumed that a gust increases from the nominal operating state of 12 m/s average wind to 24 m/s within only 2 seconds, without assuming any blade displacement, which would be possible considering the response time of the actuator system. In addition it was assumed that such a strong gust will mask the much more frequent smaller gust loads. This gust with a gust factor of $G = 2$ is assumed to appear with a frequency of 10000 over the lifetime of 20 years. Since the speed range is between 12 m/s and 24 m/s, the installation will be effected by the gusts under normal operating conditions (load case 2).

Growian is to be maintained in operation up to an average wind speed of 25 m/s. From this base wind speed, in the extreme case we can consider a gust with a gust factor of $G = 1.6$ and 40 m/s and also over 2 seconds, which occurs about 50 times during the lifetime of the installation (load case 4).

The so-called "Century gusts" of 60 m/s will probably not

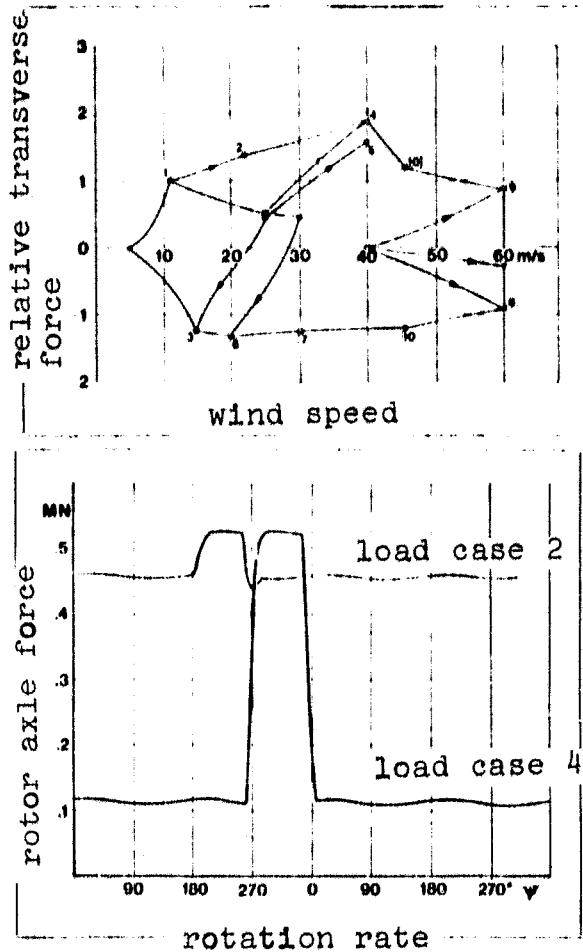


Figure 3

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Figure 4

Figure 3. Bending transverse forces at the blade root

Figure 4. Rotor load with gust.

affect Growian during power generation operations, because it can only build up from a base speed of 40 m/s. But in this case, Growian will be turned off for safety reasons and the gusts will impinge on a rotor which is standing still or rotating slowly, and its blades will be in the sailing position (load cases 8,9).

In addition to these load cases, we have specified a number of others, which could be produced from special operating situations. Because of their occurrence probability and/or the load they have to be considered. For example this includes loads due to wind speed drop, during an emergency shutdown or when the rotor is standing still and undergoing repairs.

Rotor blade loads

For the calculation of the load variations for the different load cases we used a helicopter rotor computer program which was modified for wind rotors, which allows one to represent various rotor configurations in operational states by inputting a large number of input parameters. For the 100 meter rotor we assumed a constant rotation rate, a pendulum joint, a blade angle feedback and a rectangular gust variation with a duration of 0.5 seconds for the maximum value. In order to reduce the calculation time we considered a non-elastic rotor blade. We calculated the components of the blade connection forces, the tangential clamping moment and the radial distributions of the air force components and the torsion moment. We also considered the mass forces caused by the pendulum motion. The non-rotating rotor center coordinate system is used to represent the rotor loads which is a result of the superimposed components of the forces and moments from both rotor blades. These forces have to be absorbed by the following installation components such as the rotor shaft, gears, generator, control elements and the tower structure.

Figure 3 shows the bending transverse forces at the blade clamping point referred to the nominal operating conditions, for the defined load cases as a function of wind speed. For each load case we show the load multiple of the gust load peak. Starting with an operating state with a nominal power output of 3 MW at the generator for a wind speed of 11 m/s (Point L 1), a horizontal gust with $1.37 \cdot 11 \text{ m/s}$ produces a load multiple of 1.37 (Point L2). For a higher wind speed of $v = 25 \text{ m/s}$ and stationary nominal power output of 3 MW the basic load is lower than for L1, that is only 44% or 47% in the range of permissible rpm fluctuation $\pm 15\%$. A gust with a gust factor 1.6 that is, with $v_{Boe} = 15 \text{ m/s}$ leads to the points L5 and L4 respectively with load multiples of 1.58 and 1.88. A negative gust of 10 m/s describes the load case L3 with a negative load multiple of -1.24. For the load case L 6 with -1.32, the load in the negative direction

is even greater. Above the operating wind speeds the load cases of the rotor standing still or the freely running rotor have to be considered. In the load case L 8 the 60 meter/second "Century gusts" produces a multiple of -0.92 for a horizontal rotor in the sailing position (wind sock position). L 9 starts with slow free idling at about 20% of rpm and $v = 40$ m/s, and the same gust produces a load multiple of 0.88. For the maintenance case L 10 the rotor is vertically fixed and the upper rotor blade is perpendicular to the flow and the incoming wind has a speed of 45.6 m/s and the blade is stationary (according to skyscraper building restrictions DIN 1055) and the load multiple is ± 1.2 depending on the wind direction.

Figure 4 shows a comparison of the time variation of the rotor axial force P_{Nr0} for load cases L 2 and L 4, and we assume a rectangular gust with a duration of 0.5 seconds.

The frequency criteria applied to the various operating states or load cases which give a relationship to the fatigue strength of the materials used, result in about 2×10^4 load /43 reversals for the frequent load case L 1. For the infrequently occurring load cases L 2 and L 3 this gives about 10^4 load reversals. For the rare L 4 - L 10 cases, 500 or less load reversals are assumed.

Blades Structure

It was not possible to exclusively use glass fiber plastics (GFK) for the rotor design, because the requirements for separating the eigen frequencies of the tower and the rotor with respect to the rotation rate could not be satisfied. At the same time the bending of the pure GFK-rotor blade under load was too large, and the required safety factor between the power holddown stress and the deflected blade would have been too small.

The comparison of the calculated blade weights clearly fa-

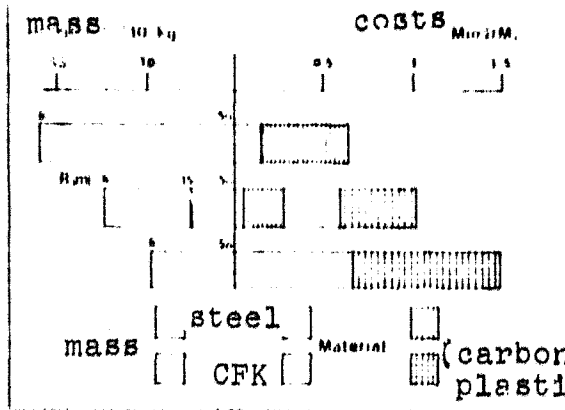


Figure 5. Masses and costs of different blade designs

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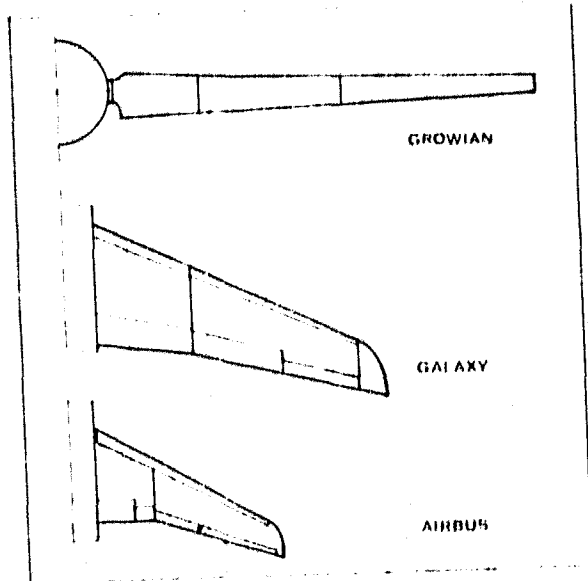


Figure 6. Size comparison with aircraft wings.

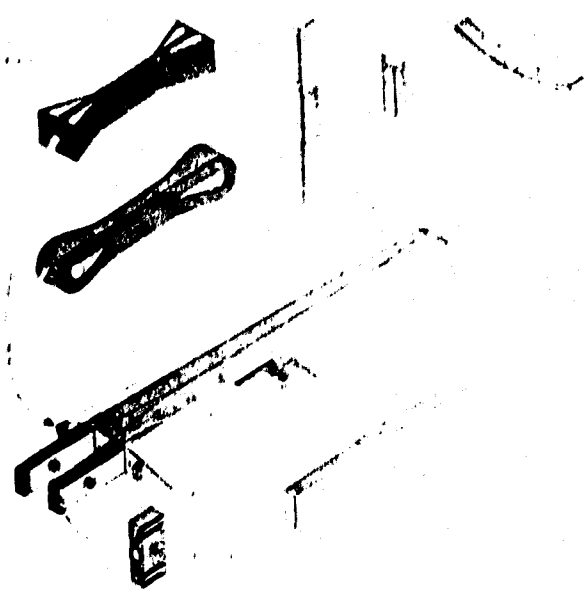


Figure 7. Test program

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vors the highly advantageous CFK material. The high cost of the carbon fiber raw material of about 140 DM/kg however leads to higher production costs of the rotor (Figure 5). On the other hand if one considers the possible mass savings for the hub, the machine house and the tower brought about the lighter rotor, these increased costs may be equalized.

In spite of the substantially higher mass, we planned an extended steel hub 15 m long for the prototype (Figure 6). In addition to its greater stiffness of the steel part, this internal part can be simply flanged to the hub and therefore offers certain advantages. The outer parts can be made from GFK/CFK using conventional methods of glider construction. The masses were 4200 kg for the central part of 15-30 meters, and 1200 kg for the outer part up to 50.2 meters.

This division was necessary in order to provide simple transport conditions and to allow a short manufacturing time, compared with wings having a metal structure such as in the airbus or with the largest aircraft in the world, the Galaxy, this problem of the Growian rotor blade becomes clear (Figure 6). A rotor length of 50.2 m is longer than the Galaxy wing, and especially has a higher aspect ratio. In addition there are the complex loads, which require a complicated blade structure.

In the analysis of all the solution possibilities of introducing forces into compound structures, it seems that the transverse force connections using a collar arm seems to be the best design at the present time. This avoids problems which occur in thick laminates, which leads to substantial force reductions in the case of Growian because of the 3 m or 2 m collar arms. /44 There are flapping bending moments as well as large deflection bending moments and centrifical forces and therefore the structure is complemented by separate spars to support these loads. The torsion loads are absorbed by the shell as usual.

The rotor blades are connected through the environmental loads more than are the stationary parts of the installation. The movable components of the wind generation plants are fielded from these loads. Temperature changes, air humidity and salt content of the air enhance corrosion. The fiber composite rotor blade can be protected by a protective layer of polyurethane. This highly elastic and weather resistant paint, which is often used on commercial aircraft, protects it against corrosion at the profile nose from the high speeds which occur on the rotor. These are caused by impurities in the air such as sand or dust.

A lightning arrester system in the spar region is required for the rotor blades made of glass fiber and carbon reinforced plastics (GFK and CFK). The CFK spar members conduct electricity and therefore are endangered by lightning. A fine network of aluminum mesh in connection with lightning arresters in the nose and at the trailing edge protect the CFK primary structure against failure in the case of a lightning bolt.

An extensive test program has demonstrated the functional capability of the system (Figure 7). In addition to determining the pure material characteristics for samples with wall thicknesses of up to 30 mm we also tested the components. We made comparisons of the loadability of force introduction elements using parts made of GFK and CFK. The largest CFK part made was a collar arm with a length of 7.5 meters and a mass of about 550 kg made by the firm Schempp-Hirth Kirchheim. It was subjected to a dynamic load test by the (IABG) company. After the program which simulated 100000 gusts at twice the nominal wind speed and 100 "Century gusts" we found no fatigue phenomena during subsequent fracture tests.

At the conclusion of all of these tests we can look upon the prototype of the composite rotor blade as a design which could be produced according to the present state of fiber composite technology.