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Guidelines to Interpret Results of Mechanical Blade Test

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"Guidelines to Interpret Results of Mechanical Blade Test"

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30 pp. 0 fig. 0 refs.

Abstract:

This report shows the interpretation of full scale rotor blade test results and describes the engineering testing models and coeficients for any feasible rotor blade design, in order to accept and to certify any final manufactured blade as an allowable product, fit for use and working with a completely sucurity during all the windturbine´s lifetime.

This work was carried out at the Wind Energy División of the CIEMAT.DER and it is based on the author´s technical experience in this field, afther many years working on testing blades. Also, this paper contains results of the "European wind turbine Standars II" relevant to the European Project : JOULE III R.D. where the Wind Energy División took part as participant too.

"Directrices para Interpretar los Resultados de Ensayos Mecánicos de Palas"

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30 pp. 0 fig. 0 refs.

Resumen:

Este trabajo muestra como interpretar los resultados de un ensayo de pala de aerogenberador a escala natural, como debe ser el modelo de ingeniería para su ejecución y el valor de los coeficientes y permisibles, para poder certificar con garantía una pala recien fabricada de manera que presente un funcionamiento seguro durante toda su vida de servicio en el aerogenerador.

El trabajo ha sido realizado por los autores expertos a través de muchos años en ensayos de palas de aerogeneradores de todos los tamaños. Este repor también refleja los resultados de los Standars elaborados dentro de Proyecto Europeo JOULE III : "European wind turbine Standars" en el cual tomó parte la División Eólica del CIEMAT.DER.

INDICE

1. INTRODUCTION

The objective of this section of the report is:

* To disseminate the experience of CIEMAT towards the interpretation of full scale rotor blade test results and the use of engineering models for rotor blade design.

* A description of by CIEMAT accepted deviations of principal parameters between theoretical design and actual determined values in the tests. The deviation is expresed in a nom dimensional form, namely:

$$Error = \frac{M_m - M_t}{M_t} \bullet 100$$

where M_m = measuring magnitude and M_t = theoretical magnitude.

- Comments, by CIEMAT, on the IEC-1400-1 partial factors to check whether the test result is acceptable to reach the required safety level.

When the CIEMAT criteria are met, indicated by the test blade error values which should/must be less than the values reflected in this document, the design/blade is adequate for certification.

The error margin, accepted for certification, is adequately adjusted so that the product has a guaranteed quality/reliability, but at the same time the margin is not that low that this makes the product excessively expensive.

2. NEED OF TESTS

It is well known (see e.g. the s&fat project, [I, 18]) that wind turbine rotor blades test are performed to compare the measured values with the theoretical determined values. Another objective is to determine the safety level of an individual blade including the effects of (series) fabrication. The answer on the question how representative is the result of one test for the series produced blades depends on the manufacturing process characteristics. This implies that the test is not representative when the manufacturing process is changed throughout the series production.

The reasoning and rules given in this section are based on the fact that the results obtained from a full scale rotor blade test are only valid for a series produced group of blades of which the manufacturing procedure, neither the quality of the materials nor the structural design has changed.

Thus, the validity of the test is based on the validity of the test self, but also on the quality of the manufacturing process of the series production.

VERIFICATION OF BLADE IS ESSENTIAL AND ITS LATER CERTIFICATION

3. CAUSES OF THE DIFFERENCES BETWEEN THE BLADE THEORETICAL CALCULATIONS AND THE TESTS RESULTS

One has to accept that there will always be a difference between measured properties of actual structures and theoretical determined values of those properties.

In this report it is shown how to interpret the engineering model verification tests results

By a test, we can verify several structural parameters of a given structure. However the determination of such parameters is not exact, obviously in every test and measurements some errors are included.

There are many causes of these errors which appear in four fundamental phases of the design (verification) process:

A) Modelling, in which a engineering model is elaborated.

B) Manufacturing, in which the blade is fabricated.

C) The Test, in which several tests for the design parameters verification are carried out.

D) Interpretation of tests results.

Itemising the causes that contribute to the error(s) we come to the following:

A) Modelling phase

A-1) Codes to calculate the aerodynamic loads and the wind turbines performances. This is essential in order to get an acccurated theoretical loads, aproached to the real ones.

A-2) Structural codes, finite elements programs for composite structures.

A-3) Finite elements type selected to model the rotor blade.

A-4) To model the blade by finite elements means check codes capacity criteria and CPU time. Total number of elements and distribution and fineness of the mesh for these elements along of blade. Boundary conditions.

A-5) Number load application points (or localized straps) and its distribution along the wingspan, that represent the load envelop, as test loads in order to determine some structural parameters, according to specification test. Localized pulling point in every load section.

A-6) Knowledge of the used materials and of the aerodynamic parameters and coefficients.

B) Fabrication phase

B-1) Intake and quality control of materials.

B-2) Factory conditions, cleanlines, hygiene, air-conditioning in order to fulfil the fabrication processes requirements.

B-3) Laminate quality, criteria of weight content both in fibber and resin. Possible air inclusion, resin excess.

B-4) Mold tolerance with regard to the calculations and the blade plans.

B-5) Laminated adaptation to the mold. Spring bag phenomenon, wrinkled, three-dimensional effects by internal stress in the laminate. Internal dimensions of pieces.

B-6) Adhesive, in case that exist blade stuck parts.

B-7) Process repetitiousness. Possibility that in a series production rotor blades are not identical e.g. due to deformations during post-curing, worker's manual skill for the manufacturing process.

C) Test phase

C-1) Bed stiffness of the Test Plant. .Inadequate stiffness of the blade´s anchorage structure.

C-2) Precision of the loads systems and in associated equipment. Adequate loads aligning.

C-3) Accuracy of the strain measure systems and in associated equipment.

C-4) Accuracy of the accelerometers and in the vibrations measure equipment.

C-5) Loading time. Load profiles versus time.

C-6) Temperature measures.

C-7) Selected measured blade zones. Stress concentration phenomenon. Wrong Saint Venant principle application. Ignornace about the kind of stress to be measured in a determinated zone. In general, to have a bad experience in tests.

C-8) Selection and precision of the strain gauges employees and in associated equipment. Strain gauge assembly selection type. Thermal and hygrometric compensation.

C-9) Precision registering in all data type.

D) Interpretation phase

D-1) Manufacturer to test analyst correct communication about the blade mass, geometric, and elastic characteristics.

D-2) Mathematical data treatment precision. Numerical analysis.

D-3) Test analyst experience. Though this characteristic is valid for the others factors also.

As to be expected there are a lot of possible sources of errors. In spite of these possible errors the total effect will remain restricted when the test is performed correctly and the test can be of great use for the blade and windturbine manufacturers.

4. CLASSIFICATION OF STATIC TEST

A static test must be complete, i.e. must cover all areas of the structural knowledge. This is based on the experience acquired in projects such as AWEC-60 (WEGA I), S&FAT (JOULE), etc. We consider it convenient to divide (or to classify) the static general test activities into the follwing subtasks (see Table I)

TABLE I

STATIC TEST	Natural vibration test	
	Elasticity test	Equivalent stiffness
		Influence coefficients
	Static load strength test	Limit load
		Ultimate load

Not shown in table I, but before executing the static test, we must perform some geometric and mass measurements on the test specimen. After these measurements are carry out, we will proceed to perform the static test, i.e. all the activities as shown in Table I.

The first is the vibrations dynamic test, since the blade has not been loaded and is not deteriorated by any destructive test yet.

The next test is the elasticity test to obtain the elastic and structural blade properties.

The last test is the Static load atrength test, which consist of the limit load and ultimate load test. During these test the resistance of the blade against the load is measured. During the ultimate load test the blade (local) strains might be above the linear elastic allowable strain, even break the blade.

5. BLADE IDENTIFICATION MEASUREMENTS

As already mentioned, before testing a blade, so called specimen identification measurements have to be carried out. The objective of these measurements is to check the conformity of the blade with the design specifications.

In this paragraph the minimum measurements are indicated that must performed the blade is tested. In table 2 the measurements are listed incluiding the maximum admissible deviations with the design specifications, acording to the criteria of CIEMAT.

The aim of this work is that the given results are valid for any type of blade.

TABLE 2: DETERMINED PREVIOUS MEASURES

Measure	Maximum Admissible Deviation	Affected Causes
Geometric and mass properties		
Blade wingspan	err. < 0.1 %	-Mold tolerance -Blade compound integration
Chords distribution along the blade span	err. < 0.2 %	-Mold tolerance -End work, finish edge and blade polish
Total twist (absolute) value between the first aerodynamic section and tip	abs. err. < 2°	-Mold tolerance -Post-cure twist phenomena
Bolt hole diameter tolerance of the blade root connection	abs. err. < ±0.5 mm	-Commercial drill bits -Cutting speed and erosion
Bolt hole centre location tolerance of blade root connection	abs. err. < ± 1 mm	-Placement drilling machine -Machine tolerance
Blade weight	error < ± 5%	-Blade fabrication processes -Reproduction process not exact
Blade centre of gravity position	error < ± 5%	-Blade fabrication processes -No exact reproduction process

These are a minimum requirements, on errors of geometric and mass characteristics, to be fulfilled to proceed the test

Obviously other characteristics like e.g. the blade longitudinal moment of inertia in relation to the rotor shaft, etc. could also be specified, but these are of less importance. Due to the fabrication process —lamination of perfectly established layers— the blade weight as well as its centre of gravity position are (usually) very similar to the theoretical values. In the practice the similarity between test and theoretical determined values of the blades longitudinal inertia moment is guaranteed.

6. NATURAL VIBRATION TEST. (EIGENFREQUENCIES)

Is well known that the objective for the vibration test is to determine the blade's natural frequencies and overall dumping.

6.1. Natural Blade Frequencies

The objective of the natural frequency test is to determine possible blade resonances problems, e.g. using a Campbell diagram. On the other hand, the stiffness distributions will be determined by subsequent test (elasticity test). In a blade test there is necessary to determine the first two flap and lag frequencies.

TABLA 3: ADMISSIBLE DIFFERENCES BETWEEN THE ACTUAL AND THEORETICAL DETERMINED VALUES OF BLADE FREQUENCIES (CIEMAT CRITERIA)

Frequency	Percent of error
1st of flap	< 12 %
2nd of flap	< 13 %
1st of lag	< 18 %
2nd of lag	< 20 %

These tolerances are justified by the stiffness and mass distribution variations, and also by considerations based on the Campbell diagram.

Due to fact that the natural torsion frequencies are (much) higher than the natural bending frequencies, it is not required to obtain this value.

6.2. Damping

To determine both damping components, aerodynamic (viscous) and structural, is not an easy task. Also, the results vary quite a lot due to e.g. the test methodology and/or due to the temperature of the blade.

According to the CIEMAT criteria the damping error must be less than 50%

Error < 50 %

(See S&FAT document, vol II: [18]).

7. ELASTIC TEST

The elastic test is composed by two subtasks:

7.1. Stiffness equivalent test.

7.2. Influence coefficients test.

The objective of these tests is to know the principals elastic and structural blade characteristics. These tests can be execute one after following the other or simultaneously.

7.1. Equivalent stiffness test

The objective of this test is to obtain the equivalent stiffness, i.e. EI, in several blade sections. The equivalent stiffness can be determined by assuming one or more uniform cross section(s) ending up witt te same behaviour as the real stiffness distribution.

It is difficult to establish criteria in this field because it is related with the blade sections which can vary a lot and due variations of its construction system.

And so, the admissible error in this case is taken conservatively and can therefor be applied to any type of existing blade in the market, because the given value is based in elastic considerations.

When the error, between the design and test values, exceed this value difference is considered to be unacceptable.

The maximum error value can be put in the form:

$$\frac{EI_R - EI_T}{EI_T} \cdot 100\% < 10$$

Where EI_R = actual test stiffness, and EI_T = theoretical stiffness value.

Namely the maximum error value must be less to the 10 %.

Due to the fact that the information recorded by strain gauges is based on small area, the theoretically calculated stiffness, EI, compared to a measure bending moment based on a strain gauge couple may deviate.

Consequently we propose to place several strain gauge couples in each of the interesting sections.

The minimum number of strain gauge couples to determine the equivalent stiffness in a section must be two. And the minimum number of blade sections to check the equivalent stiffness must be four.

The strain gauge couples must placed between 25 % and 50 % of the profiles chord, counting from the leading edge.

The span wise location to check the stiffness are in table 4.

TABLE 4 : SPAN WISE LOCATIONS TO MEASURE THE EQUIVALENT STIFFNESS (IN BLADE WING SPAN PERCENTAGE)

Section	1%	$(3\% \leq x \leq 5\%)$	35%	70%

The location x=1% takes into account the characteristic phenomena of stress concentration in the blade-hub zone.

The sections with $(3\% \leq x \leq 5\%)$ takes into account the blades handle (neck) behaviour.

The location 35% and 70% of the span are distributed along the blade wingspan.

As we can see there are a number of error sources for this test, the errors are associated with:

* The strain gauge itself and its local placement on the blade
* The determination of the materials characteristics
* The engineering model.

7.2. Influence coefficient test

When it is valid to use the linear elastic theory then the reciprocal-work theorem of Betti/Rayleigh is valid. The reciprocla-work theorem is stated as:

The work done by the forces in the first state of loading when they move through their correspondig displacements in the second satate of loading is equal to the work done by the forces in the second state of loading when they move through their corresponding displacements in the first state of loading.

See e.g. a text book by Timoshenko & Gere [19].

In one dimensional formula form this comes down to

$$P_A u_B = P_B u_A$$

Or also by definition of a coefficient indicating the displacement in k direction at a location j due to a certain load applied at point i in other direction l. We will symbolise the coefficient by C_{jl}^{ik}.

Generally, the displacement, $_{ik}$, is due to an arbitrary force, F^{jl}, applied in the j point, in the l direction, in the i point and in the k direction. Mathematically we have:

$$\delta_{ik} = C_{jl}^{ik} \cdot F^{jl}$$

For a determined test we could simplify the prior expression for a single load, F, that acts in a given point in certain prefixed direction, for example in flap direction. The expression (7-1) is now:

$$\delta_{ik} = C^{ik} \cdot F$$

The criteria of CIEMAT, to get a good indication of the blade production quality, requires only one test. This test is to measure the displacement $_{ik}$ resulting of a single load, F, in one point and one direction. This test is assumed to be sufficient and is much more simple than the more general test.

The flap direction is elected, due to the fact that this direction has the lowest stiffness and thus the displacements are larger and, in consequence, the influence coefficient could be measured with a high precision.

For certification the maximum error in the influence coefficients must be less than the 8%

error < 8%

A maximum error less than 8 % is correct because it implicates a good similarity between the theoretical engineering model and the test results.

Other error sources must also be to considered, such as:

The lack of precision or resolution in the measurement systems. These systems could be a simple as, e.g., threads, rulers, etc.

The variability of basic material properties, resulting in different laminate properties alteration or,

The errors in the engineering model.

However, such errors are less than associated with the equivalent stiffness measurement, because in the last case strain gauges are used ehich detect localy.

Furthermore the closer we get to the blade root, where the deflections are very small, the larger this last type of errors becomes. The measurement is not valid when the measurement systems error is of the same magnitude as the error in the deflection to be measured.

Consequently, when the measure systems are simple like e.g. threads, rulers, etc., they should not be used to measure the influence coefficients in those blade zones, whose X coordinate is less than 35 % of the wingspan. In such cases, to guarantee correct measure of the influence coefficients, we recommend the use of laser measurement devices of other with equivalent accuracy, whose inherent errors are less than the mentioned 8 %.

8. STATIC LOADS STRENGTH TEST

The objective of this test is to put the blade to the limit and ultimate loads to verify its strength and to obtain, furthermore, safety factor and the design reserve factor.

8.1. Limit load strength test

This test is to put the blade to the design limit load, LL_{DES}, which definition is the following:

$$LL_{DES} = PSF_{LIM} * LL_T \qquad (8\text{-}1)$$

Where PSF_{LIM} is the loads partial safety factor, and LL_T is the theoretical limit load.

Testing the blade at this load, our experience indicated that measuring 3 sections is enough. Certainly 3 sections is not a great number, but it reduces the costs of the test. To test more than 3 sections make the test unnecessarily expensive or excessively complicated.

These three sections corresponding to 0%, 35%, and 70% of the wingspan.

Analogous to this reasoning loading 3 sections is enough to reproduce the bending moments and the shearing forces envelope adequately.

The loads must be introduce in the effective shear centre for each blade section. *The maximum admissible error in shear centre determination must be less than 7% of the local chord.*

error < 7 %

For severity of static test we think that the relative static strength factor:

$$RSSF = \frac{SSF_{design}}{SFS_{test}}$$

should never exceeds 1.2, so this factor have to be limited to:

$$\boldsymbol{RSSF < 1.2}$$

8.1.1. STRESS TOLERANCES

In the opinion of CIEMAT, the admissible error values, test results compared to the pertinent (engineering) models, for a number of phenomena are indicated below:

Error tensile-compressive stress < 5%

Error bending stress < 5%

Error shear stress < 8%

Error buckling stress < 10%

Error post-buckling stress < 16%

Error micro cracking stress < 8%

8.1.2. SAFETY FACTORS

To palliate certain uncertainties of both, project and test, we utilize so-called partial safety factors.

The partial safety factor, which is a parameter that corrects theoretical and laboratory values, takes into account the uncertainty or variations, both in the loads and in the materials, in order to make the design reliable and to avoid the failure.

A review of the principals safety factors, and the values applied by CIEMAT in comparison with IEC-1401-1, table 3, is given below.

8.1.2.1. *Partial safety factor for loads,* $_F$

This factor is defined by following equation

$$F_d = \nu_F \cdot F_t$$

where F_d is the design aerodynamic load, and F_t is the theoretical aerodynamic load.

Load type	F factor
Aerodynamic	1.30
Operational	1.80
Gravity	1.10
Other inertias	1.30

The main discrepancy between the CIEMAT value and the IEC.1400-1 is in the operational load value. The value of 1.45 given by IEC, is assumed to be very low.

For loads related with transport, considering the very complex terrains (as in Spain), a V_F (transport) is introduced with and estimated value of

$$V_F \textbf{ (transport)} = \mathbf{1.7}$$

for all load types.

8.1.2.2. *Partial material factor,* V_m

This factor is mathematically defined as follows

$$f_d = \frac{f_k}{V_m}$$

where f_d is the design values for material, and f_k is the characteristic values of material properties.

Material type			
Steel			1.05
Aluminium			1.12
GRRP	Hand lay-up		1.30
	"Pre-pegs"		1.08
	Un-tempered laminate		1.15
	Tempered laminate	without thermal slope	1.05
		with thermal slope	1.02
	Creep strength		1.60
GFRP (compaction process)	By vacuum		1.05
	By pressure with male and nut		1.05-1.20
	Pressure cooker		1.02
Glue			1.20

8.1.2.3. *Partial factor for failure consequences,* γ_n

This factor is defined as follow

$$\gamma_n \cdot S(F_d) \leq R(f_d)$$

where *S* is a stress function and *R* is a material resistance. For static test and all failure consequence types

$$\gamma_n = 1.00$$

in agreement with the IEC-1400-1 given value.

8.1.2.4. *Test load scatter factor,* ν_{su} .

$$\nu_{su} = 1.05$$

When the manufacturing process is correct the value of 1.1, given by IEC-TC88-WG8 (pag. 32), could be excessively high.

8.2. Ultimate load test

This test is to put the blade to ultimate load, UL, which definition is the following:

$$UL = SF_{DES} * LL_{DES} \quad (8\text{-}2)$$

Where SF_{DES} is the design safety factor, and LL_{DES} is the factor defined in equation (8-1).

In our opinion should be:

$$SF_{DES} = 1.5$$

The aim of this test is to obtain

$$SF_{DES}^{TEST} = UL^{TEST}/LL_{DES} \qquad (8\text{-}3)$$

The load applied to the structure through this test is increase step by step, until eventually the ultimate load, UL^{TEST}, that according to our criterion, is the load under the which the structure endured at least 10 second.

From equation (8-3) yields SF_{DES}^{TEST}. And this test concludes the blade adequacy if:

$$SF_{DES}^{TEST} \geq SF_{DES}$$

Evidently that implies

$$UL^{TEST} \geq UL$$

We are believing that the SF_{DES} minimum value must be great than 1.5 in order to certify a blade

$$\boxed{SF_{DES} \geq 1.5}$$

According to our criterion the elected sections for both tests, ultimate load and limit load strength one, are equals. *Namely, corresponding to the 0%, 35% and 70% of the wingspan.*