The TENTORTUBE: an innovative improvement of a passive tip mechanism

P.A. Joosse

Stork Product Engineering B.V.

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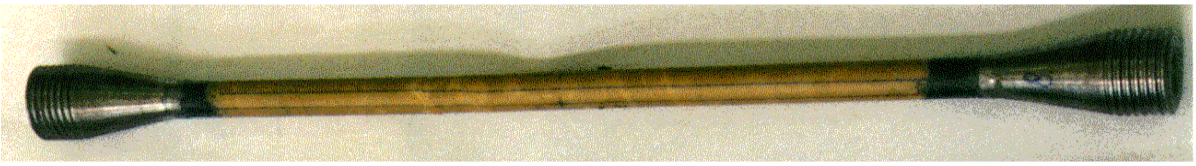

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1. ABSTRACT

For variable speed wind turbines it is possible to perform both a power control and a safety function using centrifugally controlled tips. Present mechanisms (screw-cylinder/spring type) are expensive and maintenance critical. A possible solution to these problems can be achieved with a so-called TenTorTube (Tension-Torsion Tube): a tube with inherent coupling between tension and torsion.
The objective of the project is to obtain reliable predictions on performance and stability and information on costs and applicability of the configuration by developing and testing a full-scale TenTorTube tip mechanism.

The initial proposed design of the TenTorTube was a long slender tube made of aramid fibre reinforced epoxy with an inherent coupling between tension and torsion. During the first phase of the project it became clear that the fatigue properties of aramid/epoxy were dramatically bad due to a creep-like behaviour. Tests on carbon/epoxy tubes showed an considerable increase in design strength, but not in torsional stiffness.
Results of non-linear prediction of aeroelastic stability and performance showed poor stability and power limiting capabilities, mainly caused by the low torsional stiffness. Wind tunnel tests were carried out using a 2 degree of freedom model with an active control loop to simulate the TenTorTube properties like stiffnesses, damping etc. The wind tunnel tests confirmed the results obtained by the aeroelastic stability predictions.

The torsional stiffness requirement can not be met with the initially specified wind turbine configuration (250 kW - 2 bladed). An alternative (conceptual) design was generated, but was rejected. A parameter study showed that for 3 bladed turbine configurations with an increased ratio between maximum rotor speed and rated rotor speed, a feasible TenTorTube design was possible. Tower fatigue loads will however be larger which will result in more expensive towers for medium-sized wind turbines.

Resulting from the promising test results on carbon/epoxy tubes flexible resin systems have been evaluated. A more flexible resin in combination with a T300-type of fibre has been selected with improved fatigue strength and acceptable elastic properties.
Based on the promising material properties and the aeroelastic predictions it was decided to continue the project by designing, producing and testing full-scale tubes. The design of the tubes resulted in a realistic tube length (roughly 3 m). Unfortunately the tube manufacturer did not succeed in producing tubes according to spec within the time scheduled, so the tubes could not be tested and evaluated.

2. PARTNERSHIP

The TenTorTube project has been co-ordinated by SPE. The following partners were involved in the project:

Aerpac Special Products B.V.
attn. J. Lemmen
P.O. Box 167
7600 AD Almelo, the Netherlands
phone: +31 546 549 549
fax : +31 546 549 599
e-mail: j.lemmen@aerpac.com

ECN-RE
attn. Dr. J.W.M. Dekker
P.O. Box 1
1755 ZG Petten, the Netherlands
phone: +31 224 56 4278
fax : +31 224 56 3214
e-mail: j.dekker@ecn.nl

IPA Composites NV
attn. Joris van Raemdonck
Waaslandlaan 38
B-9160 Lokeren, Belgium
phone: +32 9 348 78 23
fax : +32 9 348 76 85

Stork Product Engineering B.V.
attn. P.A. Joosse
P.O. Box 379
1000 AJ Amsterdam, the Netherlands
phone: +31 20 556 3485
fax : +31 20 556 3556
e-mail: p.joosse@spe.storkgroup.com

University of Edinburgh, dept. of Physics
attn. Dr. F.H. Barns
King's Buildings, Mayfield Road
EH2 3JZ Edinburgh, United Kingdom
phone: +44 131 650 5233
fax : +44 131 650 5902
e-mail: F.H.barnes@ed.ac.uk

3. PROJECT OBJECTIVES

The aim of the R&D program on tension-torsion tubes, which includes this project and related national projects, is to develop an innovative, reliable and cost-effective passive tip pitching mechanism. Based on this aim, the objective of this Joule project is to develop and test a full-scale TenTorTube tip mechanism, resulting in an aerodynamic stable wind turbine configuration and reliable information on the applicability, costs and benefits of the TenTorTube mechanism.

For variable speed wind turbines passively controlled tips can be used to perform both a power control and a safety function. The tips are activated by the centrifugal load; as soon as the centrifugal load becomes larger than a pretension the tips act as a pitching mechanism and limit the aerodynamic power. For passive tip mechanisms often a metal screw cylinder and spring are used. Main drawbacks of these tip mechanisms are large mass and complexity (due to e.g. the required height), required maintenance and high costs.
These drawbacks are not encountered if mechanism is replaced by a fibre reinforced Tension-Torsion Tube (TenTorTube). The TenTorTube is a long slender tube and is placed inside the hollow tip shaft. A TenTorTube uses the coupling between a tensional load and a torsional deformation that can be obtained with anisotropic fibre reinforced plastics.
The main advantages of using a TenTorTube for tips mechanisms, instead of a screw cylinder and spring, are relatively lower mass and costs, more compact, less complex, maintenance free and improved reliability.

For small wind turbines inherent tension-torsion coupling may be possible as a full span pitch mechanism. This may serve as the first step towards a flexible blade with inherent tension-torsion and/or bending-torsion coupling, the rotor of the so-called 'ultimate' wind turbine.

In the recent past the first steps towards the utilisation have been taken. The objective of *this* project is to cover the remaining white spots:

- aeroelastic stability,
- full scale manufacturing,
- full-scale testing.

Aeroelastic stability is generally seen as a potential problem for rotor structures with a low torsional frequency. For a TenTorTube blade an additional coupling occurs. This topic will be addressed both theoretically and experimentally and will result in a validated analysis tool and an aeroelastic stable configuration within the range of operation.
Manufacturing of a full scale blade and TenTorTube is needed for the full scale test and gives valuable information on the design, production aspects and costs. A short testing period is foreseen to obtain a power curve, tower head loads and strains of the TenTorTube in realistic conditions.

The project is thus intended to supply the remaining data required for the commercial implementation of the TenTorTube and demonstrate the applicability and feasibility of the tube for a passive tip mechanism.

4. TECHNICAL DESCRIPTION

4.1 Introduction

In this chapter the activities will be discussed in detail in the order of execution. To give a clear overview a short summary is given first of the material testing as accomplished in separate (Dutch national and privately funded) projects (0). Although not part of this Joule project, it is reported here briefly because of the effect of the test results on the feasibility of TenTorTubes and on the activities in this Joule project. In parallel to this aeroelastic predictions were carried out (0).
As a result of these two activities an intermediate evaluation (0) became necessary. While it became clear that the original TenTorTubes became unfeasible, at the same time alternative mechanisms were searched for, but rejected. The feasibility would only remain possible if positive results could be accomplished in three fields: materials (increased fatigue strength), system constraints (lower required torsional stiffness) and validation of prediction tool (with wind tunnel tests). These items are discussed in chapters 0 to 0. From these activities it was concluded that a material with potential high fatigue strength was available, a configuration with a 3-bladed rotor with TenTorTubes would be feasible and the prediction tool was validated.
A tube of acceptable geometry was therefore designed (0) to be tested in fatigue (0). Unfortunately production problems (delivery of the mould, see 0) prevented testing and evaluation of the tubes, so the (fatigue) strength and tension-torsion performance could not be validated.

4.2 Fatigue testing on small tubes

From former feasibility studies it was concluded that aramid/epoxy material would be preferable: the torsion deformation at (axial) failure was the highest and thus resulted in the shortest and less expensive tubes. Initial static testing of hand lay-up tubes confirmed this.
The use of fibre reinforced plastics for a TenTorTube deviates from conventional use for wind turbine rotor blades because of the off-axis fibre loading. To rule out uncertainties on the fatigue behaviour a fatigue testing program was initiated (funded by NOVEM).

Test tubes were produced using 8 layers of UD prepreg tape (20°/-70° orientation), in an inflatable pressure bag production technique with a steel fixture to the test machine. The composite tubes had a free length of 420 mm, an inner diameter of 12.2 mm and a thickness of approx. 2.1 mm.
The tubes have been tested statically and in tension-tension fatigue (R=0.1), with a given pre-twist. Static failure occurred in the tube, at the layer interface (delamination), at approx. 17.3 kN. Between 0 and 4 kN the force-elongation curve was almost linear. Fatigue testing was started at 12 kN, with an expected lifetime of 10^5 to 10^6 cycles. During the fatigue test vast and premature degradation was encountered. Fatigue life was only 4300 cycles and due to permanent deformation the pre-twist was lost within 10 cycles. Only for a maximum dynamically applied load below 4.0 kN an acceptable behaviour is observed.
Short cyclic tests were conducted to find the strain level at which permanent deformation occurs, this is the starting point of this fatigue induced failure. This ‘elastic strain limit’ [5] was found at only one quarter of the mean static value. For this allowable strain level the tube length would become unacceptable (>> 5 m).

Due to a better interfacial bond between fibres and resin and a higher transverse strength of the fibres, a carbon/epoxy composite TenTorTube is expected to perform better with respect to fatigue. This has been verified by performing additional fatigue tests and short cyclic tests. The allowable load before encountering creep related fatigue problems is about twice as high for carbon/epoxy tubes as previously found for aramid/epoxy tubes.

The fatigue tests have led to the important observation that for the TenTorTubes (lay-up [20/-70]) creep is strongly related with fatigue. It is likely that failure of the composite tubes starts with debonding at the fibre-resin interface and in case of aramid fibres also with "debonding" of the fibre filaments. Once debonding phenomena start, less surface area will be available for a proper stress distribution, and this causes stress concentrations and hence further debonding etc. The macroscopic effect of this is creep. To our knowledge the relation between time dependent behaviour and fatigue life has never been so clearly observed and reported for aramid fibre composites.

4.3 Aeroelastic stability predictions

Both the dynamic behaviour of the TenTorTube-rotor and the interaction with aerodynamics are non-linear, so standard linear aeroelastic stability analyses was expected to be of limited value. Therefore, a non-linear simulation tool has been used for aeroelastic predictions, based on Hamiltonian equations of motion [4]. In this tool, a wind turbine is defined as a multi-body system with rigid elements connected by hinged springs. A particular feature of the used tool is that - besides the turbine configuration - only the generalised moments have to be specified. The remaining parts of the set of equations of motions are recursively generated by the code at every time step, therefore inertial coupling effects like e.g. Coriolis forces need not be modelled explicitly. This offers high flexibility in changing the configuration and number of degrees of freedom, but effects of individual effects can not be monitored directly.

A baseline configuration of a wind turbine equipped with an aramid/epoxy TenTorTube mechanism was chosen, after which parameters were varied to observe the influence on the simulation results.
Main turbine characteristics of the baseline configuration are: 250 kW variable speed turbine with a 2 bladed, 30 m rotor (Aerpac APX-29 alike), 30% tip length and a TenTorTube torsional stiffness of 76 Nm/rad. Because the tube torsional stiffness is much lower than the blade pitching stiffness, the elastic axis is assumed to be on the pitch axis. The elastic axis and the centre of gravity axis of the tip are located at 25% chord position.
The configuration was modelled as a multi-body system containing of 12 dof's: 1 rigid body rotational dof (the drive-train), 1 pitching dof at the blade tip and 10 dof's for flapwise bending dynamics (7 for the fixed blade and 3 for the tip). No lead-lag blade stiffness was incorporated in view of the relative high stiffness in that direction compared to the flap-wise and pitch-wise directions.
For every blade segment, the aerodynamic forces are calculated using standard blade element momentum theory, dynamic inflow, optional dynamic stall and Prandtl tip correction.

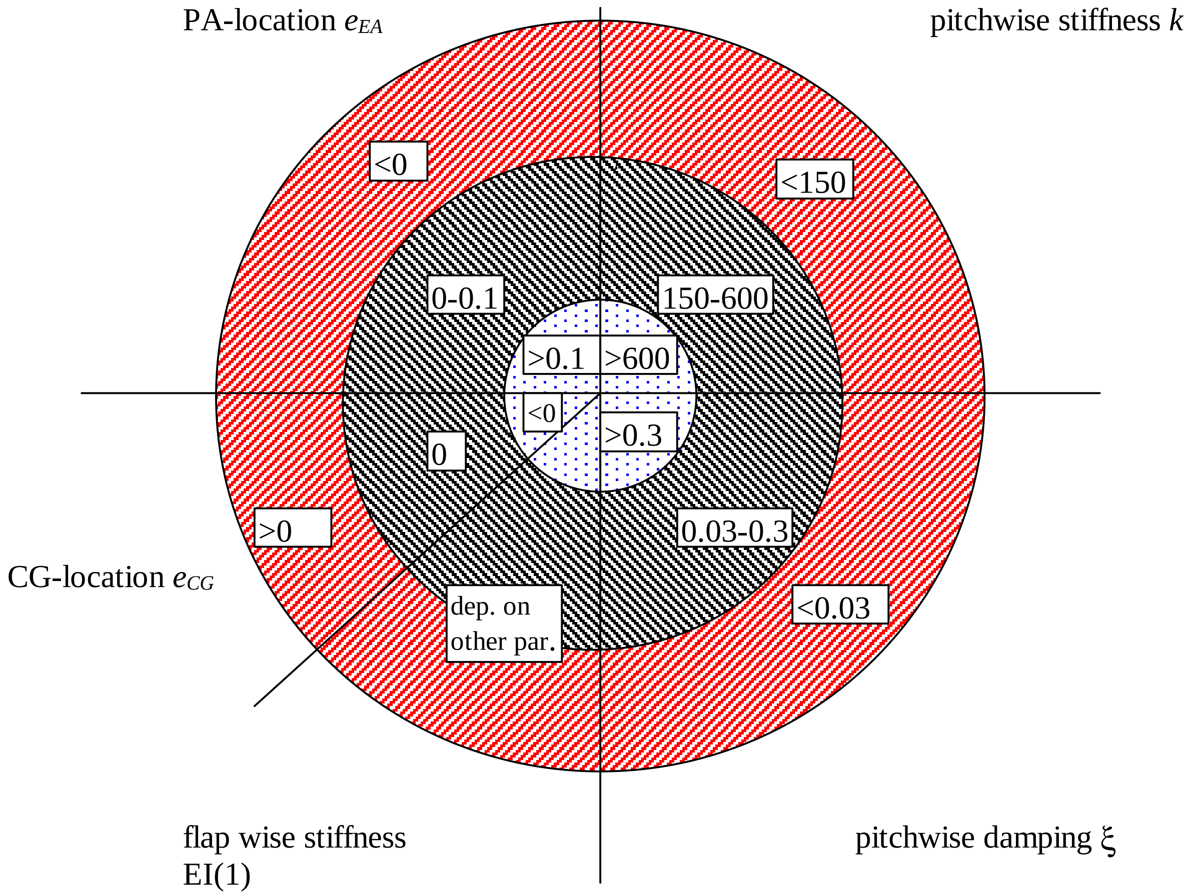

figure 1: Effect of parameter setting on stability

parameter values cause severe risk of instability/ extreme limit cycling /flutter

certain combinations of parameter values possibly preserve stability, but checks and accurate adjustment is needed.

strongly reduced risk of instability; only one or two of the parameter having an appropriate value in this segment suffices for stable behaviour.

The simulation results of the baseline configuration show poor stability and performance for activated tips. Although pitching stiffness is rather low, this result is not according to linearised aeroelastic analysis of pitch-flap coupling [2], promising stable tip behaviour. Therefore a more elaborate sensitivity analysis was needed not only to examine the influences on behaviour, but also to find the origin of the observed instabilities. The consequences are globally indicated by figure 1 and correspond with common aeroelastic insights.

The most critical parameter appeared to be the pitching stiffness. Increasing the stiffness to values above 600 Nm/rad resulted in stable tip behaviour and better power control performance, although coupling between pitch mode and second bending mode has to be avoided. Assuming that a realistic torsional stiffness is used other parameters can be used for fine-tuning. A high (artificial) pitch damping, modifications of the blade flapping stiffness distribution (low stiffness near the blade root) and shifting the centre of gravity and pitch axis to the leading edge (relative to 25% chord location) has a stabilising effect.
For the baseline configuration the tension-torsion coupling performance is completely

overruled by the aerodynamic moment at the tip.

From the results of the predictions, it can be concluded that the best performance and stability is found for parameter values outside the range which is feasible with the initially proposed TenTorTube configuration. The very low pitch wise stiffness (torsional stiffness of the TenTorTube) is the main cause of the poor stability level and power limitation performance.

4.4 Intermediate evaluation

In order to establish to what extent the torsional stiffness can be increased while maintaining the concept of a fibre reinforced TenTorTube the following analyses is done.

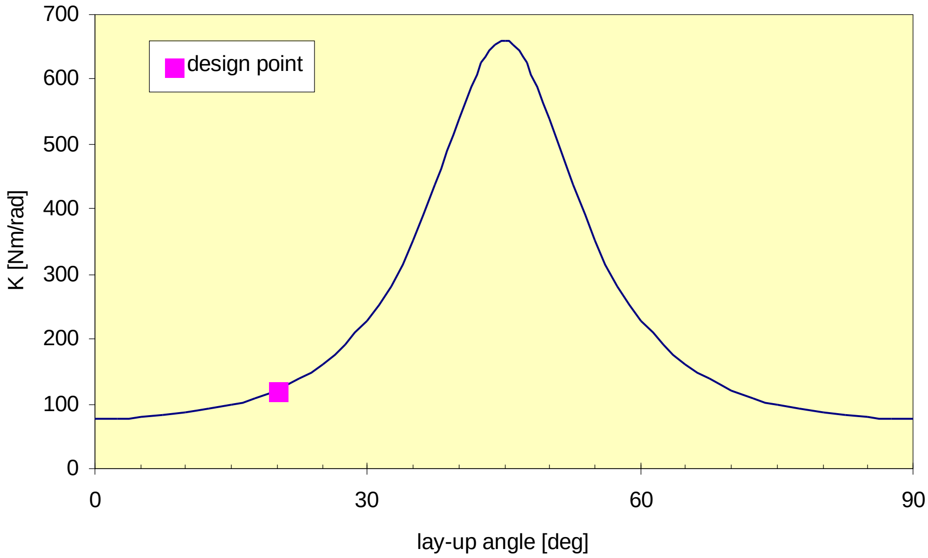

figure 2: Torsional stiffness as function of the lay-up angle (CFRP tube with constant geometry)

Both the specific angle of twist induced by centrifugal load and torsional stiffness are a function of the material compliance's (resp. a_{16} and $1/a_{66}$) and the tube diameter. A small tube diameter is beneficial for the specific angle of twist, but leads to a low torsional stiffness.
The *design point* as indicated in figure 2 gives the torsional stiffness for a TenTorTube which fulfils the requirement with respect to tension-torsion efficiency for already a considerably long tube (about 7.5 meters). The torsional stiffness at the design point is close to 120 Nm/rad, which is far below the requirement of 600 Nm/rad (see figure 1). As can be observed, the lay-up angle has a large influence on the torsional stiffness. By increasing the angle θ from 20^o upward, the torsional stiffness can be increased significantly. However, at the same time the allowable load on the tube will decrease and - more importantly - the tension-torsion efficiency will diminish. In conclusion: by increasing the lay-up angle θ, a larger torsional stiffness can be achieved at the cost of an even larger TenTorTube.

The foregoing has led to the conclusion that another type of TenTorTube design is needed for the reference configuration. Subsequently, a new conceptual design has been generated by SPE. This design is more like a mechanism, where the torsional deformation due to the centrifugal load and due to the torsional moment are separated. This provides the possibility to combine a high tension torsion efficiency with a large torsional stiffness.

Due to the high development risks and the fact that the new design could not be considered as a first step towards an ‘ultimate’ blade, it was decided not to pursue the alternative design within the present Joule project.

Considering all results obtained so far, it can be concluded that although the fatigue properties of a carbon/epoxy TenTorTube are far better than those of an aramid/epoxy tube, the needed length of a realistic TenTorTube is that large and the torsional stiffness that low, that the composite tension-torsion tube with an inherent coupling between tension and torsion is no longer feasible for the chosen WT configuration (250 kW - 2 bladed).

4.5 Optimal Fibre Resin Combination

In fatigue CFRP tube specimens showed to be a factor 2 better than aramid/epoxy (see 0). Therefore, this CFRP material has served as reference for further material improvement.
To achieve a good balance between tension-torsion efficiency and shear stiffness, a value of G_{12} is required in between 2 and 4 GPa. At those values the tension-torsion coupling is high (so the tube length small) while the torsional stiffness of the tube is still reasonable. G_{12}, in turn, is a function of the fibre volume fraction and the shear stiffnesses of the constituents. For strength reasons, the fibre volume fraction should be in the order of 0.5 to 0.6, which can be normally achieved with a tape-winding technique or similar techniques with prepregs.
For increased fatigue strength, high values of the following material properties are needed:

- Ultimate shear strain of the composite, yielding the requirement of a highly flexible resin system, in combination with a good bonding between resin and fibres;
- Inter laminar shear strength, making HT carbon the preferred fibre type;
- Glass-transition temperature.

On basis of the requirements above, several suppliers have been invited to provide material data of their advanced CFRP prepreg systems for evaluation purposes. Especially with ACG (Advanced Composites Group) fruitful discussions on their available prepregs have taken place, followed by additional material testing for only a small financial compensation.

From the comparison it showed that the resin system greatly affects the tension-torsion efficiency, probably due to differences in shear stiffness.
On basis of these results, the ACG MTM60 / HTA7 prepreg system is selected with a fibre volume fraction of 0.60. The HTA7 fibre is comparable to the T300 fibre. Compared to the reference system the torsional stiffness will be somewhat higher and the tension-torsion efficiency slightly lower. This material combination has a high glass/transition temperature and shear strain, that will probably lead to high fatigue resistance. For ease of manufacturing, the MTM60 shows lower viscosity, leading to a high fibre fraction in the resulting tube.

4.6 Wind Turbine Application Range

The objective of this work package was to establish the configuration limits for a ‘composite’ TenTorTube passive tip control mechanism.
A large number of parameters are governing the operation of a turbine with a composite TenTorTube. These are related to:

- the tube itself (e.g. fibre angle of the laminate, fibre and matrix material: elastic properties and strength, geometry: length and diameters),
- the blade (e.g. tip mass, length of the tip, rotor and tip geometry, aerodynamic properties of the blade profile) and
- the (operation of the) turbine (e.g. power and dimensions of the wind turbine, number of

blades, survival wind speed, rated and maximum rotor speed, required torsional stiffness to assure aeroelastic stability)

Some of the above mentioned parameters are mutually dependent, e.g. the elastic properties of the composite tube are dependent on the constituent materials and the fibre angle.

The large number of governing parameters make a full parametric optimisation a very time consuming and thus expensive process. Initial analyses indicated that the choice of a 3-bladed WT with an increased ratio between maximum rotor speed and rated rotor speed would have a positive influence on the TenTorTube design. Using these initial results a baseline wind turbine configuration has been identified, important parameters are given below.

300 kW electrical power output
3 bladed, 30 m rotor diameter
Aerpac APX29 blades / tip length 25 %
max. rotor speed: 1.8 x rated
minimum pitch stiffness: kphi=500 Nm/rad
lay-up angle: 24°
design strength: si=65 Mpa

The search for the minimum length of the TenTorTube has been performed using 'spider diagrams' in which the sensitivity of one variable for a number of other parameters is given graphically, see e.g. figure 3 for the tube length.

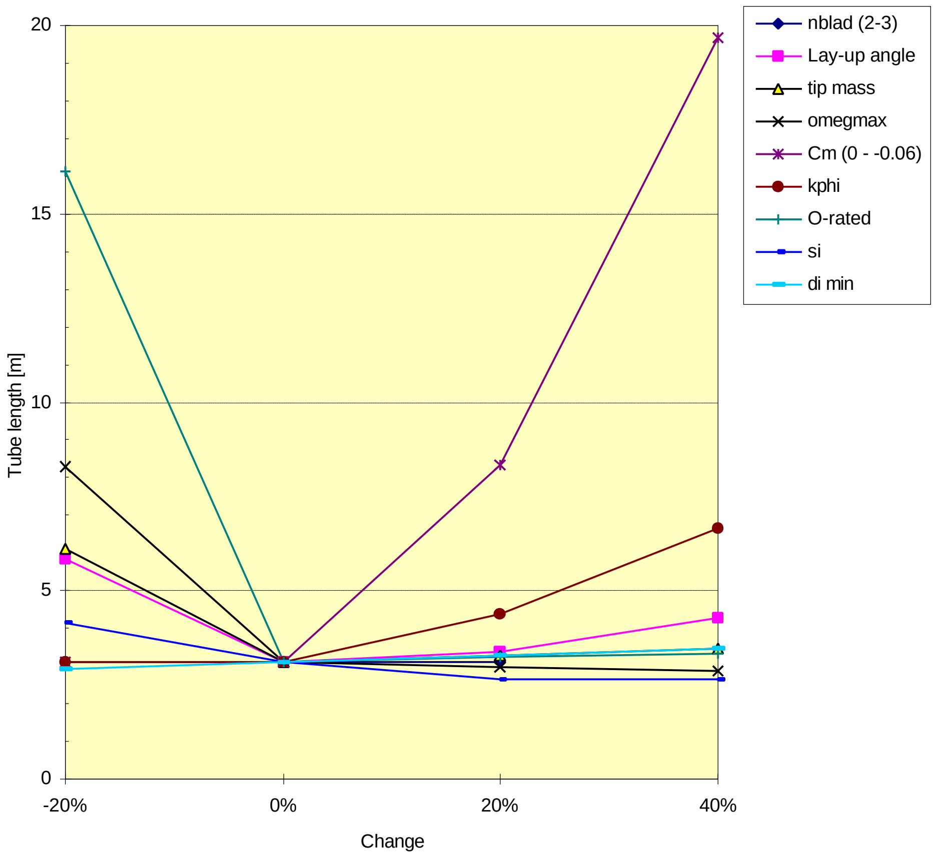

figure 3: Spider diagram for the tube length

The optimal tube length for the baseline configuration, using the material properties obtained from the testing of the CFRP TenTorTube specimens (chap. 0), is 3.09 m. The corresponding outer diameter of the tube is 40 mm. From figure 3 it follows that the TenTorTube design is very sensitive to the rated rotor speed and the aerodynamic moment coefficient C_m of the blade profile (preferably close to zero), on the other hand an increase in material design strength has only limited effect on the tube length. Calculations also showed that up-scaling should not pose many problems.
More accurate load calculations on the newly defined turbine showed a 10-20% increase in tower fatigue loads at foot centre. For stiff-soft towers, which are the norm for medium sized turbines, the tower will become heavier and more expensive. For higher towers (soft-soft) the extreme load becomes more important, hence the impact on the mass and costs of the tower will be significantly less.

4.7 Wind Tunnel Testing

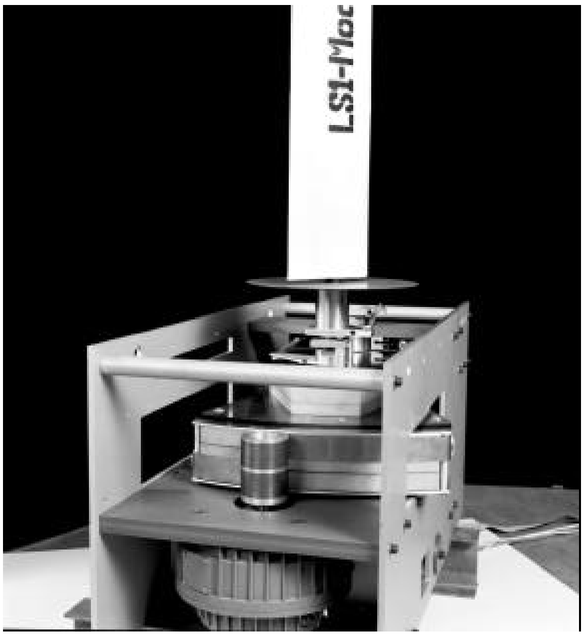

figure 4: Assembled pitch-flap rig

At the University of Edinburgh, a range of 2 degree-of-freedom systems with aeroelastic characteristics similar to the proposed passive TenTor wind-turbine control system have been tested in the closed circuit wind tunnel of the Fluid Dynamics Group.
The already available 2-degree-of-freedom, pitch flap rig (see figure 4), required extensive modification (mainly to the controllers) to allow it to perform the tests for this project whose parameter range was well outside that of the original rig specification. The active control system allowed the stiffness, damping and inertia of each mode to be independently selected, a feature that would have been difficult if not impossible to achieve with a passive rig. Variable gust loading was simulated using a disturbance foil upstream of the test model.

A total of 4 test foils have been built and tested, one of symmetrical section and three representative wind turbine blade sections (taken from the Aerpac APX29 blade). To start with the static aerodynamic characteristics of the tests foils have been examined for all foils. Subsequently, a wide range of tests have been conducted to examine the effect of the various system parameters on coupled stability.

The main test conclusions obtained are as follows:

- Stall flutter seems to be the dominant cause of divergent instability. Reduced frequency ranges are consistent with this phenomenon and will be similar at full scale.
- Pitch damping has the largest single effect on system stability as might be expected. Damping factors as low as 10% of critical prevented divergence at a blade pitch angle of initially -15°. Flap damping has only limited effect.
- Increasing pitch inertia (and thus stiffness to maintain frequency ratio) has a strong

positive influence on stability.

- Pitch axis location has a strong influence on stability as the form of the pitch moment curve dictates the aerodynamic coupling into pitch. The best all round stability is obtained at a position near 25% c. The location of the centre of gravity has less impact.

The foregoing results have been compared with the aeroelastic simulations. In the evaluation the differences between test and prediction (e.g. influence of inertial couplings, scaling effects) have been taken into account.

In general it can be stated that agreement on the effect of the key system parameters has been achieved. The UoE tests as well as the SPE simulations show that in general, increasing pitch stiffness and pitch damping are advantageous in preventing instabilities (flutter). No classic flutter was encountered in UoE test which corresponds with the result of SPE simulations concerning 1^{st} mode bending.

The Hamilton simulations are more complete from a point of view of structural dynamics and the wind tunnel tests are more complete for the instationary aerodynamics. As instationary aerodynamics are almost impossibly to model, it should not be a purpose to try to include these phenomena in the simulation tool too; tests are just the only way to reveal them and are always supplementary to simulations.

4.8 Design of a full-scale TenTorTube mechanism

For the most promising material (ACG MTM60/HTA7) and the turbine configuration (see 0) a tube has been designed for the full-scale fatigue test. These values differ only slightly from those given in 0. The optimal tube length for a (20°,-70°) CFRP laminate is approximately 3.10 m (effective length). The corresponding outer diameter of the tube is 40 mm, the inner diameter (12 mm) is determined by the manufacturing process.

No additional torsion or shear force will be applied during the test of the tubes. Due to the Tension-Torsion characteristics of the tube, a torsional load is also introduced in the end fixing. The magnitude of this load w.r.t. the tension load has been neglected in the dimensioning of the end fixing.

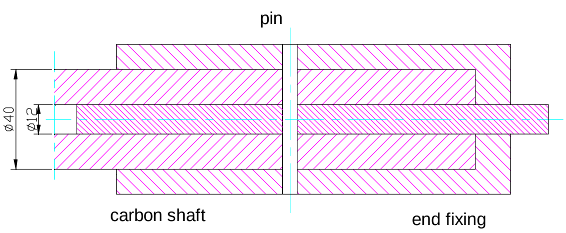

figure 5: Selected end fitting

The interface with the available test rig is given by a screw connection with thread size M30 * 1.5 with a thread length of 30 mm. This implies a metal end fixing. Different concepts for the end fixings have been discussed, e.g. a geometrical locking concept, fully-bonded concepts and combined bonding-bolting concepts. Geometrical locking results in a complicated production, bonding was expected to be complicated because of a tension component in the bonding layer. According to [1] a mechanical way of fixing a metal part to a shaft or tube gives the most reliable connection. When combined with a bonded type of connection, also a fail-safe construction is ensured, which is especially required within the tight time schedule of the project. Repairs during the course of the fatigue test are then also possible, because a complete failure will initially never occur. The selected type of end fixing is given by figure 5.

The inside pin (the so-called "pencil"), which is bonded inside the tube along with the bonding of the outside, has also the function of positioning tool.

4.9 Manufacturing of Tubes

Before production was commenced different production methods were evaluated by IPA, after discussions with Aerpac and SPE. For previous test samples of the TenTorTubes (e.g. for the Dutch national programmes) wet filament winding was used. Due to the low fibre volume fraction and thus poor mechanical properties, this option was not feasible. The most promising methods for large TenTorTubes are blow moulding and tape winding. The tape laying process was chosen for reasons of the low initial costs and flexibility in fibre lay-up.

Trial production with a short tube (600 mm length, laminate thickness of 8.5 mm applied in one production step) resulted in buckling of the fibres in the cross section of the tube. It was therefore decided to limit the added thickness in one production step to 1 mm. To enable production of the real tube (with a total length of almost 3.5 m) in horizontal position the bending of the tube must be restricted. IPA decided to do this by pre-tensioning the steel mandrel. A production set-up was designed and made for the pre-tensioning of the steel mandrel while allowing a rotation freedom. This was accomplished with an I beam (with low torsional rigidity) and bearings.

figure 6: Detail of production: winding of prepreg tape

The manufacturing process has become as follows:
Around the pre-stressed steel mandrel UD Carbon prepreg tapes are wound in the correct angles to the rotating core (see figure 6) until a wall thickness of approx. 1 mm has been reached. Then peel ply and the required number of shrinking foils are applied. The total structure of core with prepregs and the supporting structure is placed in an oven at 140 °C during 25 minutes. After curing, the foils and the peel ply are removed. This procedure is

repeated until the required outside diameter of 40 mm has been reached.

The metal mandrel was expected to be easy to remove from the resulting tube since the mandrel decreases more in diameter than the cured tube. During the first test this was falsified: the steel tube could not be removed without breaking the tube. Simple calculations showed that the steel mandrel could stay trapped due to the small cavities allowed by fabrication tolerance. Therefore a new steel mandrel with h6 tolerance (instead of h7) is needed. IPA ordered a mandrel with higher tolerance mid August 1998 but reported by the end of September that the specified length of the mandrel (roughly 3.5 m) could not be obtained in due time, only production of a 2800 mm tube might be possible. Production and testing of a short tube would complicate the technical evaluation and questions on the feasibility of producing long tubes would remain. For this reason the project was terminated.

4.10 Fatigue testing of full-scale TenTorTube

A test plan has been generated by ECN, with input from SPE, for the fatigue testing. Since the type of testing has been changed from testing a full-scale wind turbine rotor to testing isolated tubes, the location for testing was re-considered. It was decided that the Stevin laboratory of the Delft University of Technology is more suited for this type of testing.

Four identical tubes should be manufactured from CFRP according to a design made by Aerpac and SPE of which three were to be tested. The following tests - as summarised in table 1 - should be made.

tube	aim	input	expected	comment
1	operational strength test	maximum tensional force kN 74	expected torsion degrees 58	tension force to be applied in test from 0 to maximum in 11 steps and back in 2 steps, with each step force applied during 60 s
2	fatigue test	cyclic force kN from - to	nr of cycles	sinusoidal force with a frequency of 0.5 Hz according to a ‘sweep’ scheme given to the left. Each sweep to be repeated 100 times. Thus in total 1.1111 10^6 cycles to be applied in 26 days
		22.8 - 29.0	10,000	
		22.8 - 35.5	1,000	
		22.8 - 42.0	100	
		22.8 - 48.5	10	
		22.8 - 55.0	1	
3	fatigue test			same as tube 2
4	reserve			to be tested only in case of unexpected failures during the test of tube 1, 2 or 3

table 1: Test scheme for the TenTorTubes

During the test 15 sensors should be measured and recorded during the test runs.

The following preparations for the test were made by the Stevin Lab:

- Design of test rig (only by sketch)
- Preliminary modifications of control and measurement software
- Ordering materials and parts for the test rig to be modified
- Making or adapting existing test rig parts

Hardware and software preparations for the data analysis were made at ECN for the executing of the data analysis of the testing, especially for the first test the operational strength test.
However the Stevin Lab was unable to execute the planned tests due of the fact that the tubes were not delivered in time.

5. RESULTS AND CONCLUSION

5.1 Review of the results obtained

Simulations on aeroelastic stability and performance of the base line configuration show poor stability and performance where it was not expected according to aeroelastic theory [2],[3]. Therefore, a more elaborate analysis was needed than was planned in first instance with the aim to determine the aeroelastic stable configuration of the passive tip mechanism. From the predictions it was concluded that the best performance and stability is found for parameter values probably being outside the range which is feasible with the initially proposed TenTorTube configuration. The very low pitch wise stiffness (torsional stiffness) of the tube is the main cause of the poor stability level and power limitation performance. Acceptable behaviour can be expected at a torsional stiffness above 600 Nm/rad.

In a partly parallel Dutch national project the fatigue properties of the initially proposed TenTorTube design based on aramid/epoxy and carbon/epoxy have been assessed. The fatigue tests show that for the TenTorTubes (lay-up [20/-70]) there exists a strong relation between creep and fatigue. Only for a maximum dynamically applied load of less than a quarter of the static failure load an acceptable behaviour is expected for aramid/epoxy material. Operation at this safe load level however leads to unacceptable long tubes.
Due to a better interfacial bond between fibres and resin and a higher transverse strength of the fibres, a carbon/epoxy composite TenTorTube is expected to perform better with respect to fatigue. This has been verified by fatigue tests and short cyclic tests to find the 'elastic strain limit'. The allowable load before encountering creep related fatigue problems is about twice as high as previously found for aramid/epoxy tubes. This results in an acceptable tube length, but the torsional stiffness of such a tube is close to 120 Nm/rad, where 600 Nm/rad is required. Hence, it was concluded, (in the first half of 1997), that a composite TenTorTube design was not feasible for the initially proposed WT configuration (i.e. full-scale test configuration).

Initial analyses performed indicated that the choice of a 3-bladed WT with an increased ratio between maximum rotor speed and rated rotor speed would have a positive influence on the TenTorTube design. In a sensitivity study all kinds of parameters (which may be mutually dependent) were varied, such as tube properties, blade geometry, turbine characteristics. The study showed that for a range of 3 bladed WT configurations with an increased ratio between maximum rotor speed and rated rotor speed a feasible TenTorTube design can be found. This result is not very sensitive to the rotor diameter.

From theory it was already known that a toughened matrix system could enhance the tension-torsion characteristics (by increasing the elastic strain limit), provided that the stiffness would not change too much. In close co-operation with material suppliers a new prepreg system was selected (ACG MTM60/HTA7) with a relatively high shear strength and improved fatigue resistance. A striking result of the material study was that the resin system as much as the fibres affects the tension-torsion efficiency.

During the wind tunnel experiments the two-degree of freedom system together with the active control system proved to be a valuable instrument. Variable gust loading was simulated using a disturbance foil upstream. Due to the constraints (e.g. no rotation) a scaled model was designed and produced with somewhat higher torsional stiffness.
The wind tunnel tests confirmed the results obtained by the aeroelastic stability predictions.

The trends from the wind tunnel tests (e.g. the effect of the location of the centre of gravity) were in line with the predictions. There were no reasons found for modifying the aeroelastic prediction model.

Considering the predictions for the optimal turbine characteristics and the promising new prepreg system it was decided at the go/no-go meeting (January 1998) to continue the programme. In close co-operation between Aerpac and SPE a tube including end fittings was designed in early April. In parallel ECN and SPE decided on the test program, which was refined by ECN. Unfortunately IPA did not succeed in producing tubes of the specified length (effective length -which is more or less the length in between the end fittings- of 3.1 m) before October. Testing of shorter tubes would not give clear answers on the feasibility of TenTorTubes for large turbines (diameter of 30 m and larger). Because there would be no time left for fatigue testing and evaluation the programme was terminated.

5.2 Conclusions

In a preceding (national) program on the material fatigue properties of composite TenTorTubes it was found that the material (aramid reinforced epoxy) that was initially defined to be the best choice suffered from bad fatigue resistance and unacceptable low torsional stiffness. Even the use of carbon fibre reinforced epoxy, though being considerably better in strength, would result in a tube of acceptable torsional stiffness.
For the prediction of the stability margins and the power performance of a wind turbine with a TenTorTube mechanism non-linear analysis are essential. A flexible, non-linear prediction model based on Hamiltonian equations of motion has been applied and validated by wind tunnel tests.
Due to the relatively low torsional stiffness (pitching stiffness) of the TenTorTube the blade is very sensitive to the aerodynamic loading of the tip and inertial effects. The needed stiffness to achieve acceptable performance and stability is hard to reach with the proposed TenTorTube configuration.

Extensive parameter variation analyses led to the conclusion that a range of 3-bladed turbines would be feasible with TenTorTubes. This being especially so, since research in co-operation with material suppliers showed that a new toughened prepreg (with a T300 type of carbon fibre) should have increased fatigue properties at an acceptable torsional stiffness.
In view of the uncertainties it was decided to test isolated tubes in fatigue instead of a whole wind turbine rotor. A test tube was designed, including the end fittings, which resulted in tubes of acceptable length (roughly 3 m. between the end fittings). Unfortunately production problems arose which could not be solved by the manufacturer in due time. Although a test plan and a test set-up were ready, no tests were possible to validate the tube characteristics and fatigue behaviour.

6. EXPLOITATION PLANS AND ANTICIPATED BENEFITS

The intention of this project was to supply the remaining information needed for a technical and economical evaluation of a TenTorTube tip mechanism.
Due to the inability to validate the material properties the feasibility of TenTorTubes for wind turbine rotor blades can not be shown. Form this it must be concluded that at present the application of this type of tube for wind turbines is not feasible.
Exploitation of the intended product (a TenTorTube tip mechanism) is therefore not foreseen.

During the project a few nice results have been achieved that may be worthwhile in the future.

- The most important result in this respect is the further development of the aeroelastic prediction tool 'Hamilton'. The present non-linear implementation has proven to be a valuable tool, offering high flexibility in modelling with acceptable calculation times. The type of stability (the phenomena) and the trends have been validated by wind tunnel tests. Future use is expected in R&D projects (presently in the Dutch national project 'STABTOOL') and for consultancy purposes.
- The wind tunnel model (2-dof) in combination with active control has proven to be a valuable tool for R&D on tip behaviour. Further developments are however not foreseen at present.
- The use of flexible matrix material has been evaluated in this project, unfortunately no tube tests were executed. The information on this type of resin will surely be used in future designs by the partners, a concrete exploitation of this result is not foreseen.

7. LITERATURE

[1] Anon.
Processing and uses of carbon reinforced plastics
VDI Verlag 1981

[2] A.R.S. Bramwell
Helicopter Dynamics
Arnold Ltd., 1976;

[3] D.M. Eggleston, F.S. Stoddard
Wind turbine engineering and design
Van Nostrand Reinhold Company Inc., 1987;

[4] Th. van Holten
On the use of Hamiltonian concepts in rotor dynamics
Proceedings of the 16th European Rotorcraft Forum, Glasgow 1990

[5] H.M. Schwencke, A.E. de Ruyter van Steveninck
The determination of allowable wall stress for glass reinforced plastics pipe by measurement of elastic deformation
Shell Plastics Laboratory, Delft, 1968