DART: DEVELOPMENT OF AN ADVANCED ROTOR FOR TILT-ROTOR

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Abstract

This paper presents the overall development status of the European Tilt-rotor hub program. This hub, which is now entering the manufacturing phase, provides unique innovative features induced by the selected concept of a small radius gimballed and homokinetic 4-bladed rotor.

This activity is organised within a consortium of 10 companies led by EUROCOPTER and including major helicopter manufacturers (ECD, AGUSTA/WESTLAND), engineering and research centres (SENER, NLR, ONERA, CIRA), major elastomeric components supplier (PAULSTRA) and a manufacturing company (SPASA).

The design activity is supported by the General Engineering calculations that will be presented briefly with emphasis on rotor performance, loads calculations and dynamics studies.

A detailed presentation of the selected rotor configuration is presented with a focus on the constant velocity joint, the cuff, the pitch control system, the yoke, and the elastomeric components.

The completion of the hub characterisation and fatigue tests is expected on March 2006.

Background

The DART rotor development is somewhat the legacy of several research activities:

- the first independent European efforts (before the EUROFAR studies)
- the recent Integrated European efforts (EUROFAR, ERICA)

Before the EUROFAR program, several European companies had imagined, designed and sometimes tested S/VTOL aircrafts (Ref [1] ,[2] and [3]). Among them, the ducted propeller concept seemed promising enough to NORD to launch the prototype 500. Flight testing in the late 60's proved the aircraft was unstable and difficult to control. Since then, the concept of tilting ducted rotor was abandoned in Europe and elsewhere, and paved the way to the tilt-rotor concept, as demonstrated by Bell with the XV3 and XV15. Shortly after Nord abandoned the ducted propeller concept, Aerospatiale started a paper study on the tilt-rotor concept (X 910).

The EUROFAR (European Future Advanced Rotorcraft) was the first integrated European effort to develop a convertible tilt-rotor. As for DART, European helicopter manufacturers and research centres joined their forces to acquire the knowledge to build a successful tilt-rotor. Emphasis was put in the aerodynamic development of the rotor (Ref [4]) but extensive work was also performed in the architecture, aircraft performance, aerodynamics, dynamics, handling quality fields (Ref [5]). It should be noted that the EUROFAR team already selected a 4-bladed rotor to bring significant improvements in terms of noise and vibrations. Several very innovative concepts were proposed to achieve the aeromechanics requirements such as the constant velocity joint, the virtual hinge offset and pitch-flap coupling, but because very little hardware was manufactured within EUROFAR, it was not possible to test full-scale these innovations.

In the past, several examples of new rotorcraft configurations were tested. Among them, we find the tilt-wing, the tilt-rotor, the ducted fan as well as several examples of compound aircraft. The only concept, which proved successful, was the Bell tilt-rotor. The development of the tilt-rotor in the U.S. was heavily sponsored by the NASA which helped gather a good understanding of the complex aeromechanics features of this aircraft.

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[1] Rotors design – DART technical manager.

Starting with the XV15, the Bell tilt-rotors have some common characteristics. They are stiff-in-plane, which means that the rotor is free from “ground resonance” type instabilities, they have 3 highly twisted blades, they are gimballed and feature a negative pitch-gimbal coupling.

The ERICA concept (Ref.[6] , Ref.[7] , Ref.[8] and Ref.[9]) was imagined to give new perspectives for the future tilt rotor design.

A small radius rotor provides safety improvement by enabling landing in aircraft mode and increases versatility by enabling take-off in aircraft mode.
A partial tiltable wing reduces the wing download and increases productivity.

Finally, a structural connection of the two prop-rotors through a tubular spar increases the safety margin.
This concept provides other advantages such as an enlarged conversion corridor and extended whirl flutter limits.

The DART rotor benefits from the EUROFAR experience, sticks to some features of the present tilt-rotor concept rotors but provide some very innovative attributes that make it suitable to the ERICA concept.

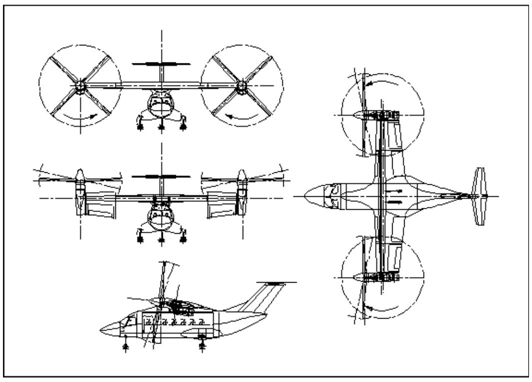

Figure 1: Three-views of ERICA tilt-rotor

Introduction

DART is one of the 6 Critical Technology Projects , partially funded by the European Commission, that were submitted under Key Action “New perspective in Aeronautics” promoting the programme of Competitive and Sustainable Growth in the 5th Framework programme.

These projects are respectively:

- DART, for the design, manufacturing and testing of the scale 1 hub,
- RHILP and ACT-TILT, mainly for the study of the Flight Control System,
- TILTAERO, mainly for the study of interactional aerodynamics at low speed,
- ADYN, with the purpose of investigating dynamics and acoustic aspects, and
- TRISYD, concentrated on the development of the drive system.

The DART rotor hub design is being developed in the framework of the ERICA concept which provided a general hub specification in terms of rotor characteristics. They include the number of blades, the rotor radius, the mean chord, the pitch-gimbal coupling, the rotor tip speed for all flight configurations, the engine power, the maximum thrust and a specification for the overall rotor weight.

The biggest challenges in the design of a 4-bladed gimballed rotor for a tilt-rotor are the achievement of a low pitch-gimbal coupling and the design of a constant velocity joint compatible with the rotor architecture.

DART organization

As for the other CTP’s, DART faced several organisational challenges.

The first challenge was to insure within the CTP a good common understanding of the tilt-rotor features and an efficient communication system. This was addressed with several tools, such as Common Design Offices, involving all partners responsible for design, workshops and usage of FTP sites enabling large and efficient information exchanges.

The second challenge was to insure consistency between CTP’s and a good overall integration. This was insured with the organisation of Tilt-Rotor workshops, some dedicated project interface meetings and integration work carried by AGUSTA.

Blade assumptions

Number of blade:	4
Rotor diameter:	7.4 m
Mean aerodynamic chord:	0.525 m
Pitch-gimbal coupling:	low negative
Tip speed in Helicopter mode:	214.3 m/s
Tip speed in airplane mode:	165.01 m/s
Engine power (A/C mode):	2400 hp
Rotor efficiency target:	0.8
Rotor Figure of Merit target:	0.86

Loads and dynamics calculations

Rotor model

When DART started, a theoretical rotor model, both hub and blade, substantiated by macro analysis and whirl flutter investigations, was provided by AGUSTA to start dynamics computations and preliminary loads calculations. As the pre-design activity provided more substantiated rotor data, such as pre-cone, yoke flexibility, elastomeric components stiffness, pitch control system layout, it became important to define a refined rotor model that would provide the foundation to the final dynamics and loads calculations.

This reference model was developed by EC who built a complete finite elements model. This model, presented in *Figure* 2 considers the yoke, cuff and blade structural data, the elastomeric components stiffness and the fittings and elastomeric components lumped mass.

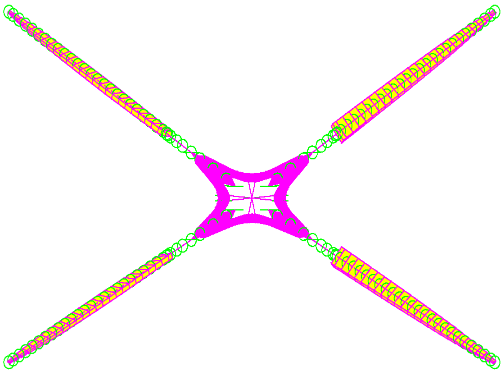

Figure 2: DART rotor Finite Element model

This model was used to compute rotor modes in vacuum for the different pitch and rotor speed configurations. The results were then compared to the beam equivalent model eigen-modes frequencies and shapes.

To enable loads and dynamics calculation with the most updated hub configuration, two beam equivalent models were built. Reference 7 provides an assessment of the two types of hub modelling: single load path and dual load path models.

It should be noted that a 3-bladed rotor exhibits only collective and cyclic modes, while on a 4-bladed rotor, reaction-less modes are also present. Consequently, dynamics tuning of a 4 bladed tilt-rotor with a wide range of rotor speed and pitch setting is very challenging.

Single Load Path Model

A single load path model (see *Figure* 3) was developed and exploited by the partners involved in loads and dynamics calculations.

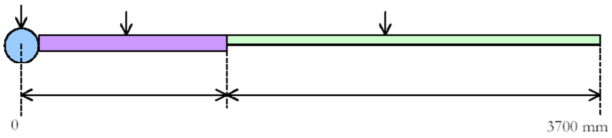

Figure 3: single load path model

As the finite elements model provides all rotor modes (collective, cyclic and reaction-less), the first issue was agreement on the mode to be considered for model tuning.

The beam equivalent model build up involved also the analysis of the pitch control system stiffness and pitch couplings. The pitch-gimbal, pitch-cone and pitch-lag couplings were determined with a multi-body tool (ADAMS) (see *Figure* 4).

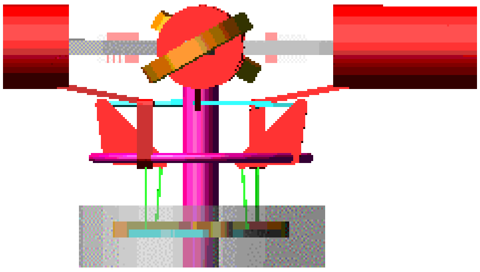

Figure 4: the multi-body model used for kinematics pitch couplings

Dual Load Path Model

For dynamics analysis, a dual load path model (see *Figure* 5 and *Figure* 6) of the DART rotor system was also established.

This model was based on a typical multi-body approach (Ref [13]): Finite beam elements represent rotor yoke, rotor cuff and rotor blades while rigid bodies are introduced for rotor control modelling. Discrete spring elements are used for the representation of flexibility for the hub gimbal joint, the blade pitch bearings and the centrifugal bearings.

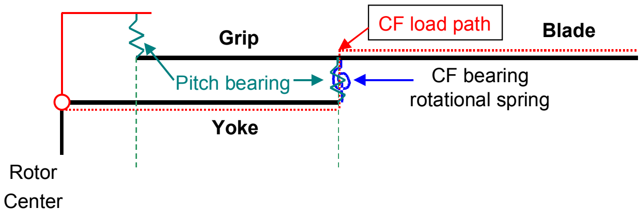

Figure 5: Dual load path model

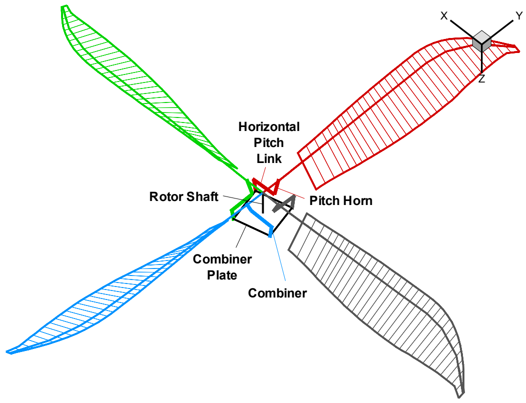

Figure 6: DART DLP rotor model

Beside the dual load path, another key point of this model is the representation of pitch control kinematics. As discussed below, the DART rotor shows an unconventional feature labelled as horizontal pitch control system. In the rotor model, this feature is considered by rigid bodies representing the almost horizontally aligned pitch links and the combiners which transform the vertical motions imposed by the swashplates and vertical rods into horizontal motions (see *Figure* 6). The modelling of the pitch control system by these means allows the adequate consideration of pitch-flap and pitch-lag couplings as well as the torque split between rotor hub and rotor controls as the horizontally aligned pitch links provide torque to the rotor system. *Figure* 7 gives the variation of the pitch-gimbal coupling parameter versus flight speed due to this kind of control system.

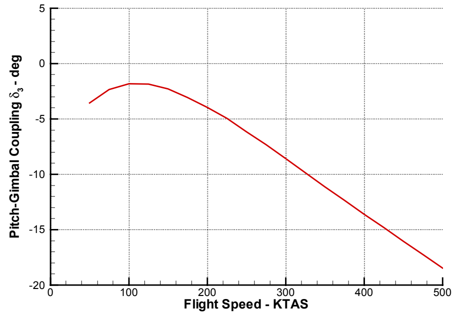

Figure 7: Pitch-gimbal coupling vs flight speed

Blade aerodynamic optimisation

The objective of the blade aerodynamic optimisation was to generate an airfoil design and a blade planform allowing for good performance both in hover and cruise.

The optimisation of the blade started from the TILTAERO design, slightly modified in order to be easily computed by all partners. The modified blade, called ADYN preliminary, is presented on *Figure* 8.

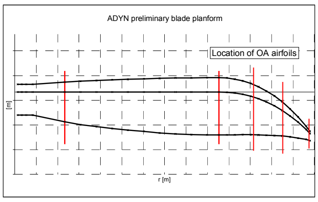

Figure 8: the ADYN preliminary blade planform

The objective of the optimisation was to further improve the hover performance of the ADYN preliminary blade while keeping its good cruise efficiency. The main steps of this process, leading to the first optimised blade, are described below:

- the chord distribution was modified for hover performance reason. It was reduced in the inner part of the blade, and increased in the outer part in order to benefit from the good behaviour of 12% airfoil
- the ¼ chord offset line was modified mainly for acoustic purpose. A double sweep was introduced (concept evaluated during the ERATO program),
- a parabolic blade tip with anhedral, dedicated to performance purpose, was also added.

Figure 9 shows the comparison between the ADYN preliminary and optimised rotors in terms of FM versus Ct/σ. Both CFD codes (*elsA* and FLOWer) predict an improved performance with the optimised blade.

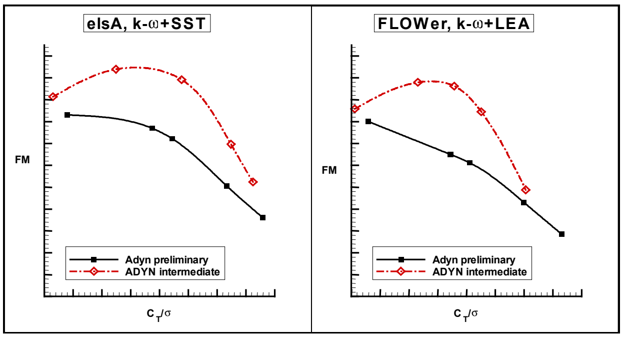

Figure 9: hover performance predicted by elsA (left) and FLOWer (right)

Even though the aerodynamic performance of this new blade was satisfying, the geometry had to be modified for 2 reasons:

- a compromise has to be reached between good aerodynamic performance and low noise rotor (in coherence with ADYN project).
- integration to the hub induced some changes in the root area.

New investigations were performed on this optimised blade in parallel with acoustic evaluations within ADYN.

- the study of airfoil influence (WHL088A6, OA407) showed limited impact on performance,
- the sweep angle proved to be critical for cruise performance,
- the twist modifications showed that an increase of twist (esp. at tip) was beneficial,

The optimised blade was selected among the candidates for both high aerodynamic performance and hub compliance.

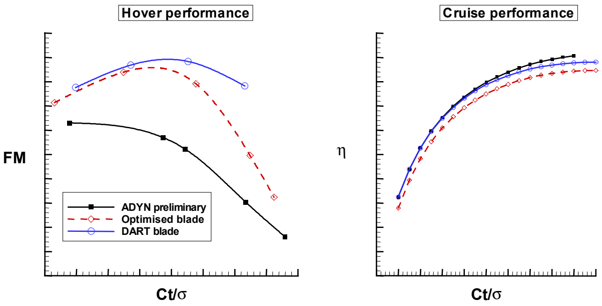

Figure 10: hover (left) and cruise (right) performances of DART blades

As plotted on *Figure* 10, the selected blade benefits from a high FM_{max} and from an important thrust margin in hover flight. Concerning the cruise conditions, the selected blade shows limited penalty compared to the ADYN preliminary.

Loads calculation philosophy

The starting activity for the design of the hub components has been the definition of a general philosophy to determine the fatigue and limit loads the rotor will experiment during its service life.
Having as reference the ERICA concept requirements, a wide set of rotor sizing cases, covering the whole aircraft operative envelope, has been defined.

For the limit load assessment, a precise strategy has been defined in order to assess the maximum rotor performances (in terms of thrust, power, inside the defined gimbal angles and rotor controls ranges).
The explored flight conditions have taken into consideration:

- helicopter mode configuration (H/C mode),
- airplane mode configuration (A/C mode),
- conversion mode configurations,
- on ground conditions,
- and special conditions

inside an atmospheric environment ranging from ISA sl –55°C to ISA sl +35°C, the P/ON and P/OFF max/min design RPMs, flight speed up to V_D and considering also a gust scenario.

For the fatigue load assessment, the operating time share of the tilt rotor has been spread in a detailed flight spectrum including:

- take-off and rescuing;
- conversion flight phase;
- cruise flight;
- manoeuvres in H/C, A/C and conversion mode tilt-rotor configurations;
- CG location and weight configurations.

All the calculation activity has been shared between the partners (AG, ECD and EC) and it has been preceded by a deep cross-correlation process between the aero-elastic codes used (HOST, CAMRAD/JA and CAMRAD II).

Isolated rotor dynamics

The challenge of an appropriate dynamic layout faced by a rotor system for tilt-rotor aircraft is complicated by two facts.

First, the airframe is significantly flexible leading to possible rotor-airframe couplings on ground (e.g. ground resonance for soft in-plane rotors) and in flight (e.g. air resonance, whirl flutter).

Second, the special design of the rotor system caused by compromises between helicopter mode and aircraft mode (high twist, variation of rotor speed) and the rotor operation under noticeable varying conditions (high thrust, low inflow and low blade pitch in helicopter mode versus low thrust, high inflow and high blade pitch in aircraft mode) leads to additional dynamic particularities for this kind of rotor system.

In order to fulfil the related requirements the DART rotor system shows the following design features:

- Stiff in-plane rotor design
- Gimbal type rotor system
- Homokinetic gimbal joint
- Four bladed tilt-rotor design
- Low negative pitch-gimbal coupling δ_3
- Hub virtual coning hinge

These features affect the DART rotor architecture significantly. As the discussion of all these features is beyond the scope of this paper, the four-bladed rotor design in combination with the pitch-flap coupling requirements for rotor stability is selected as representative case study.

In order to achieve adequate pitch-flap coupling behaviour, the design solution for the pitch control system consists in the application of almost horizontally orientated pitch control rods as the four-bladed rotor does not allow the application of conventional control systems due to space constraints. Therefore special attention has to be drawn on relative blade lag motions in the vicinity of the pitch horn significantly affecting rotor stability by pitch-lag coupling. It should be noted here that due to the stiff in-plane design no dedicated damping device has been foreseen for blade lag damping of the DART rotor system leading to low damped lag motions of the rotor.

Regarding the relative lag motions between rotor hub and rotor control, transversal hub motion is assessed to be of primary importance for rotor stability due to the nearly horizontal attitude of the pitch links.
The elastomeric parts of the hub spring are the primary source of hub in-plane flexibility. In case this flexibility is too high, the rotor hub will show significant in-plane motions introducing cyclic blade pitch feedback. In order to verify the DART rotor design, a parameter variation of the hub-spring in-plane stiffness has been performed. For the analysis of the isolated rotor, only cyclic rotor modes are affected by this kind of hub flexibility. Therefore, the theoretical studies are performed in multi-blade co-ordinates focusing only on the cyclic modes.

Figure 11 and *Figure* 12 show the modal frequencies and the damping margins of the fundamental cyclic flap and lag modes in aircraft configuration for increasing flight speeds and various in-plane flexibilities. The results are based on the multi-body rotor model. As expected, the rotor will be destabilised by increasing hub in-plane flexibility and by increasing dynamic pressure. It can be demonstrated that the dependency of frequencies on hub in-plane flexibility is mainly caused by air loads generated by pitch control feedback.

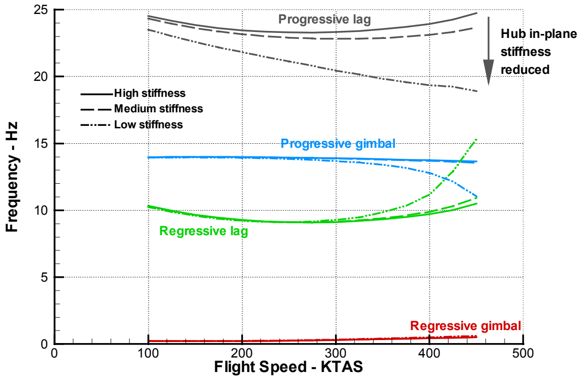

Figure 11: Cyclic frequencies: variation of hub in-plane stiffness

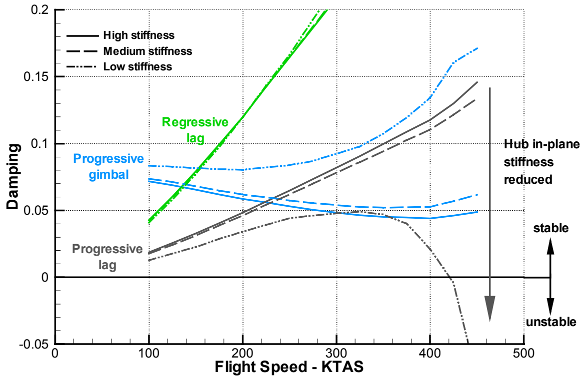

Figure 12: Cyclic damping margins: variation of hub in-plane stiffness

Whirl flutter studies

Whirl flutter instability is a key topic for tilt-rotor aircraft limiting the flight envelope with respect to flight speed and thus directly influencing the profitability of such kind of vehicles. The ERICA concept (Ref. [6]) aims on the usage of rotors with small diameter in order to reduce the whirl flutter phenomenon significantly.

Regarding the wing structure, the ERICA concept shows an innovative design of the wing by the following three main components:

- Fixed wing ranging from y=±0m to y=±4m: The fixed wing is attached to the fuselage and builds the support of the torque tube.
- Tiltable wing ranging from y=±4m to y=±7m: The tiltable wing is supported by the torque tube and can be rotated independently from the nacelle.

- Torque tube ranging from one nacelle to the other: The torque tube provides a structural connection of both nacelles and controls the nacelle angles.

Therefore, redundant load paths exist for bending in vertical and chord-wise direction for the fixed inboard section as well as for the tiltable outboard section of the wing. Nevertheless, the analysis of the structural dynamic characteristics of the wing demonstrated that the fundamental airframe modes are comparable to those of more conventional wing designs.

The results shown below are based on the DART rotor definition of the pre-design phase. *Figure* 13 and *14* present whirl flutter predictions based on a rigid rotor model (only gimbal degrees of freedom) and symmetric airframe modes for max. TOW. For simplicity, no wing aerodynamics was taken into account for all presented whirl flutter results. As typical whirl flutter phenomenon an unstable wing vertical bending mode is clearly visible in figure *14* for flight speeds above 300 KTAS.

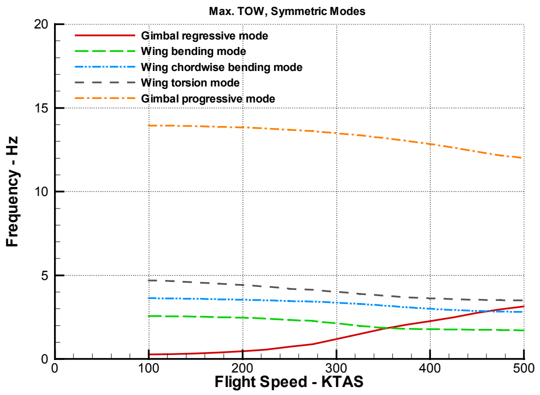

Figure 13: Modal frequencies: rigid rotor

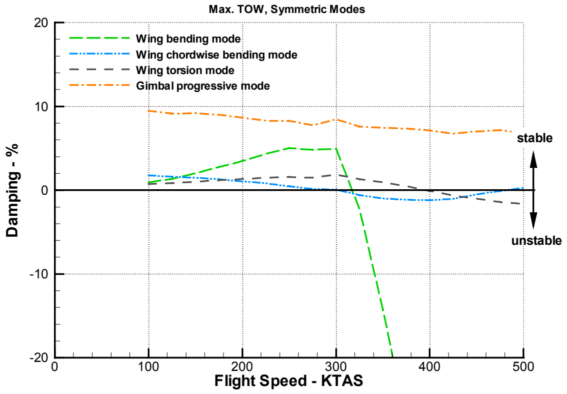

Figure 14: Modal damping margins: rigid rotor

In case of an elastic rotor system, the whirl flutter instability disappears as shown in *Figure* 15 and *16*. During the on-going progress within the DART project, these predictions have to be consolidated with respect to updated rotor and airframe data. For experimental verification, the ADYN project will analyse in depth a related wind tunnel model by theoretical and experimental means.

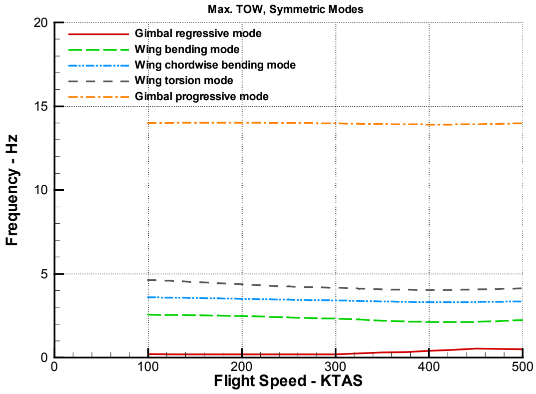

Figure 15: Modal frequencies: elastic rotor

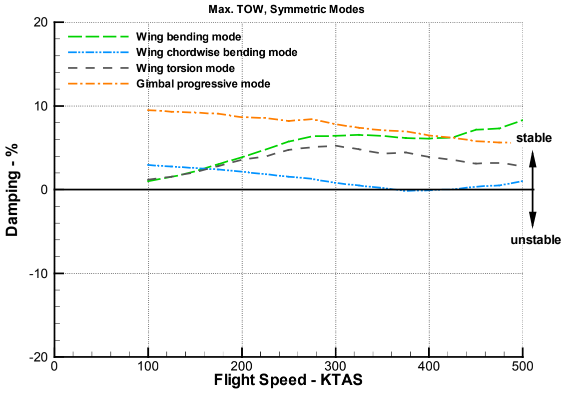

Figure 16: Modal damping margins: elastic rotor

Vibration optimisation

A numerical optimisation procedure to produce preliminary structural designs of a rotor blade was performed by WHL. Blade and hub strains, control loads or fuselage vibration can be minimised using a gradient-based optimisation procedure that alters a simplified model of the internal structure of a rotor blade. The inertial and stiffness characteristics of the blade are altered by varying the width of the nose moulding, the thickness of the spar sidewalls and thickness and width of a trailing edge stiffener. The radial distributions of thickness and width are typically described by seven polynomial coefficients.

For this study, the blade was designed to minimise vibration in the fuselage. A rigid body assumption was made to produce the transformation of rotor hub loads to vertical acceleration at the port pilots' seat. The figure of merit that was used to assess the vibration performance of each rotor blade design, was the square root of the sum of the squares (RSS) of the vibration components. Only the loads from one rotor were used so that there could be no cancellation between the loads from the two rotors.

The blade was optimised from 22.4% radius to the tip for a forward flight at 100 kts in helicopter mode at sea level and ISA conditions.

Figure 17 shows the rigid body acceleration at the port pilot's seat for the datum blade. It can be seen that the vibratory vertical shear at 4 /Rev produces the most vibration, followed by the lag shear at 3 /Rev and the radial shear at 3 /Rev. The vertical shear is due to the 2nd flap mode.

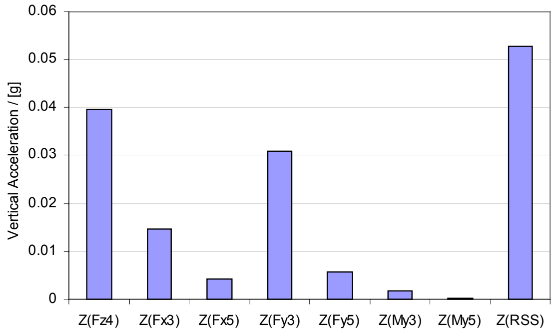

Figure 17: rigid body acceleration at the port pilot's seat for the datum blade

Figure 20 shows the breakdown of vibration for the blade designed with no constraints on the maximum first moment of mass, compared to one constrained to have an increase limited to 16% . The constraint results in only a small increase in vertical shear at 4 /Rev, and in-plane shear at 3 /Rev, due to a more efficient arrangement of sidewall material (*Figure* 18).

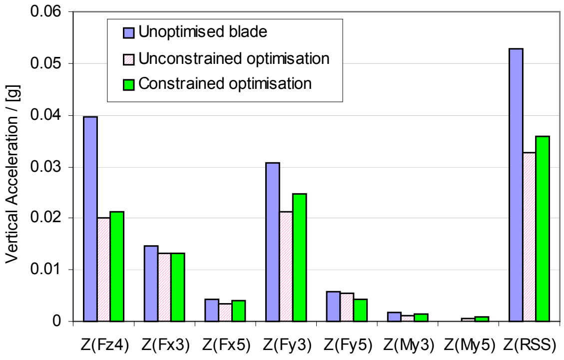

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Figure 18: Comparison of the contributions of head loads to fuselage vibration for optimised blades

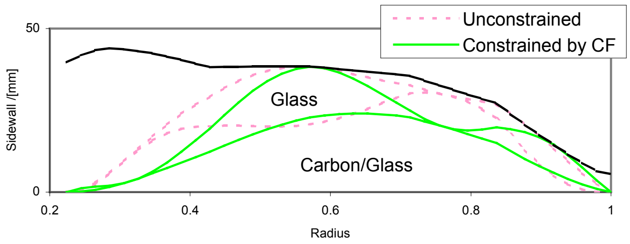

Figure 19: Sidewall thickness distribution for constrained and unconstrained blade

In a second step, the blade was optimised with a constraint imposed that the centrifugal load must not increase from the datum level. Both the sidewall and trailing edge stiffener were optimised.

Figure 20 shows the breakdown of vibration for this blade. Due to a further reduction in 3 /Rev edgewise loads, this design produces a 37% reduction in vibration with no increase in centrifugal force.

It should be noted that this design is preliminary, and as such, no strength analysis has been performed.

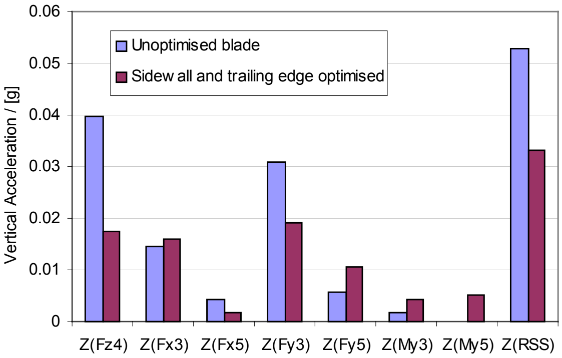

Figure 20: Contribution to vibration for a blade optimised without an increase in centrifugal force.

Elastomeric loads

Trim calculations have been performed in the conversion corridor foreseen for ERICA. The pitch bearings cyclic amplitude is given by the following expression (beta >0 when blade flaps downward):

$$\sqrt{(\theta_{1S}-\beta_C)^2+(\theta_{1C}+\beta_S)^2}$$

This can be explained by the fact that the pitch bearings are connected on one side, to the blade, and on the other side to the hub, which may tilt.

This study points out that the dynamic torsion strongly increases in the vicinity of 60° of nacelles tilt angle at high speed (*Figure* 21).

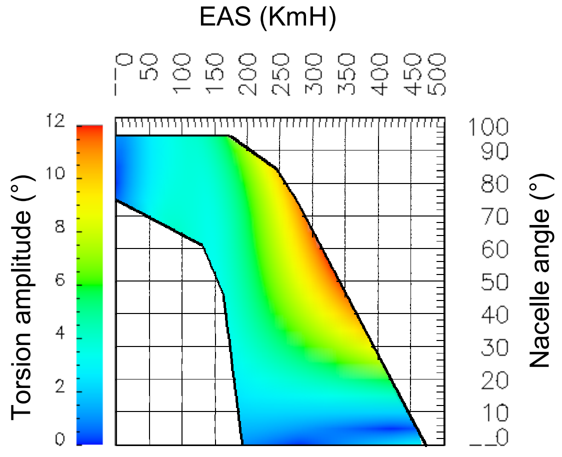

Figure 21: pitch bearing cyclic motions, sea-level, level flight, 10t, neutral CG, fully extended flaps

The same analysis has been performed for the hub-spring (see *Figure* 22).

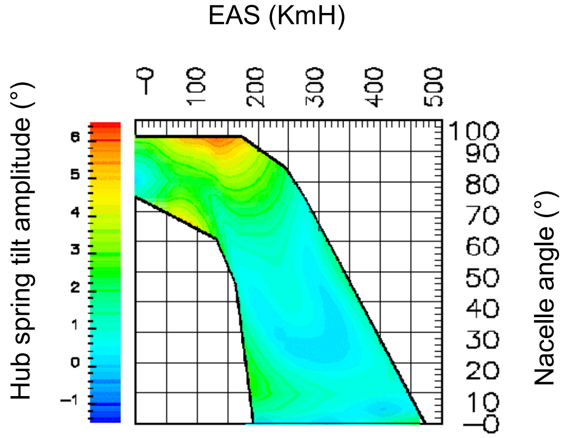

Figure 22: hub spring cyclic motions, sea-level, level flight, 10t, neutral CG, fully extended flaps

Design

The design activity started with some major guidelines for the concept development. For example, it was agreed to limit the investigations to the stiff-in-plane concept although there has been recently a renewed interest for soft-in-plane concepts. The reason for this choice is obviously to suppress any risk of ground resonance or air resonance instability even though the rotor does not exhibit any structural damping on the lead-lag degree of freedom. This concept is made possible without undue loads penalty because of the gimballed feature that limits Coriolis forces.

Another feature that was retained for the DART rotor, was the constant velocity joint to reduce blade and drive train 2/REV loads induced by the tilting of the hub.

Among the various components that are being developed for DART, two deserve particular attention:

- the yoke as it required thorough investigations due to the difficulty to reach high quality laminates with thick parts made of tough resins that exhibit high exothermal peak
- the elastomeric components which development is very challenging because of the severe environmental conditions (temperature range -50 : 50°), loading levels, ambitious weight target, heat generation (hub-spring) and buckling requirements (Centrifugal Force pitch bearing).

DART rotor

The DART rotor is presented in *Figure* 23.

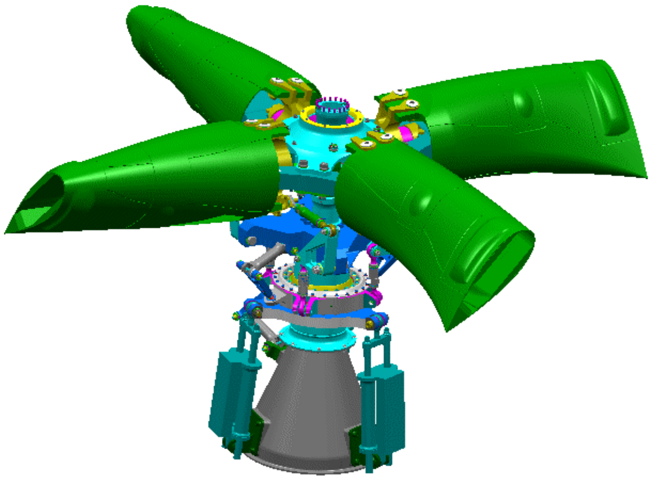

Figure 23: DART rotor

A short description of the hub components will follow.

Constant velocity joint

The constant velocity joint of the DART hub was devised with the following considerations:

- An inner constant velocity joint is preferable to carry high loads
- Installation in the hub will be easier if it features a symmetry of order 4

- a constant velocity joint designed to transmit a very high torque cannot be perfectly homokinetic.
- Vibrations generated by the constant velocity joint should have the same frequency as the dominant one (4/REV on a 4-bladed rotor)
- Simplest connection between mast and hub is achieved by drive links

The previous considerations call for a system of 4 drive links connecting the mast to the hub (see *Figure* 25).

It is however well known (Reference [18]) that such a system is hyperstatic because the drive links, while moving up an down, tend to accelerate and decelerate the rotor at a frequency of twice the rotor frequency. Thus, 2 adjacent rods on a 4 rods system would have opposite motions (see *Figure* 24).

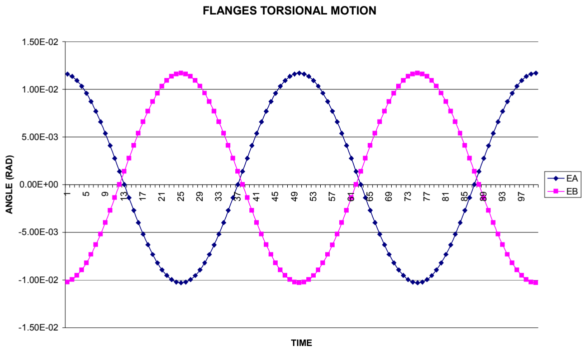

Figure 24: flanges motions for a tilted hub

Tentative to introduce a high flexibility in the drive links while withstanding the high static loads generated by torque was not successful and an innovative concept had to be developed.

Considering that 2 opposite links have motions in phase when the hub is tilted, they can be connected to a common part. These parts are called driven flanges.

Transmission of torque to the 2 sets of drive links with equal torque sharing can be accomplished by a driving flange through 4 connecting pins which hold elastomeric spherical bearings.

Figure 25: differential system assembly

In addition to the analytical investigations, multi-body tools were used to perform simulations. They demonstrate a very good performance of the constant velocity joint.

Cuff

Within DART, the blade investigations are focused on aerodynamic, dynamics design optimisation and structural analysis.

The structural analysis of the DART blade is used to substantiate the preliminary structural data used to compute preliminary loads, prepare manufacturing and enable final dynamics and load calculations

However, no manufacturing activity is planned for the blade, and means had to be found to correctly load the hub during the tests foreseen in DART.

While a trade-off study may prove an integrated blade might be preferable for a civil tilt-rotor, it was decided to develop a cuff to have a correct loading of the hub and develop technologies that could be used in the future for both a modular and integrated concepts.

This cuff is presented in *Figure* 26. Although care was taken to have a smooth surface and preliminary CFD assessment of the blade root area performed, additional aerodynamic calculations will be performed to minimise drag in aircraft mode.

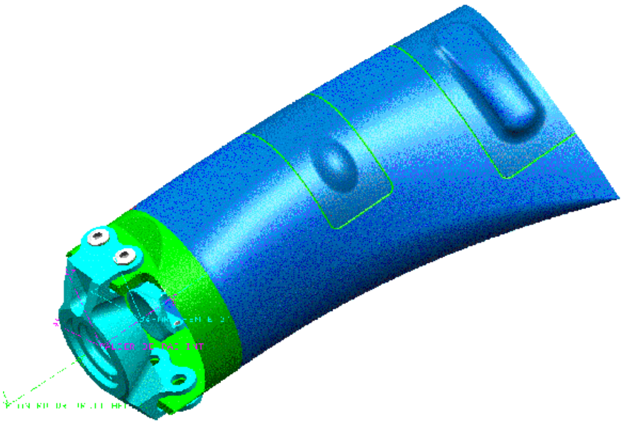

Figure 26: cuff layout

In *Figure* 27, the internal structure of the DART cuff is presented. Straps in quasi-isotropic lay-up carry the centrifugal force for two configurations of centrifugal force retention means (inner and outer).

Additionally, Carbon Fibre Composite skin layers and honeycomb are used to increase the torsional stiffness and stability.

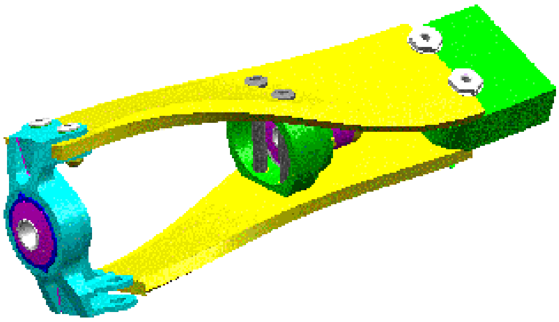

Figure 27: cuff internal structure

Pitch control system layout

The constant velocity joint being chosen and installed inside the hub, a solution had to be found to design a pitch control system with the following attributes:

- low negative pitch-gimbal coupling
- low positive pitch-cone coupling
- high precision pitch control, particularly in aircraft mode
- high pitch control stiffness
- compact layout to limit drag in aircraft mode

The proposed system (see *Figure* 28) consists of quasi-horizontal rods whose inclination provide the required pitch-gimbal coupling and vertical rods linked to a classical swashplates assembly.

Between the two sets of rods, combiners, hinged on a combiner plate, transform the vertical motion of the vertical control rods into horizontal motion of the horizontal control rod.

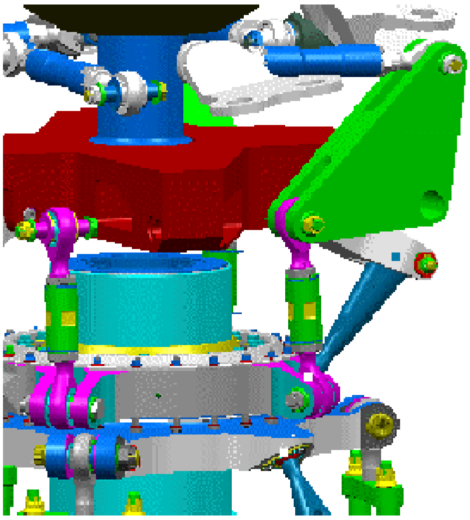

Figure 28: the DART pitch control system

To achieve the stiffness and strength requirements, design optimisations were carried by SENER.

The *Figure* 29 shows the Finite Element Model used to compute the combiner plate stiffness and stress level.

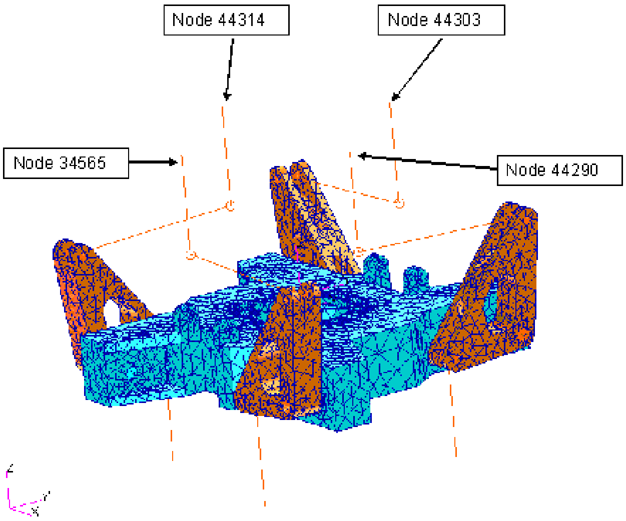

Figure 29: combiners and combiner plate F.E.M.

Hub spring

The hub spring, made of two members, connects the yoke to the mast in order to provide a gimbal degree of freedom while transmitting torque and reacting thrust and in-plane loads.

The hub spring frames were challenging parts for design because of their multiple functions.

The calculations for the static and fatigue validation of the hub spring frames have been performed using the Finite Element Method, with MSC Patran ®[2] for pre and post processing and MSC Nastran ®[3] for processing.

For the stress substantiation, several loading cases were considered:

- pre-load to avoid traction on the elastomer and to account for differential thermal expansion of the elastomeric shims
- CF reaction in combination with the yoke
- Collective and Cyclic Flapping loading at the yoke interfaces and inner pitch bearings supports.
- Collective and Cyclic Lead Lag loading at the yoke and inner pitch bearings supports.
- Drive link vertical reaction in the upper hub spring frame induced by the rotor flapping.

All these loads have been analysed and merged in a combination load case considering the worst case for every loading case. This provided a stress distribution map of the critical areas (see *Figure* 30).

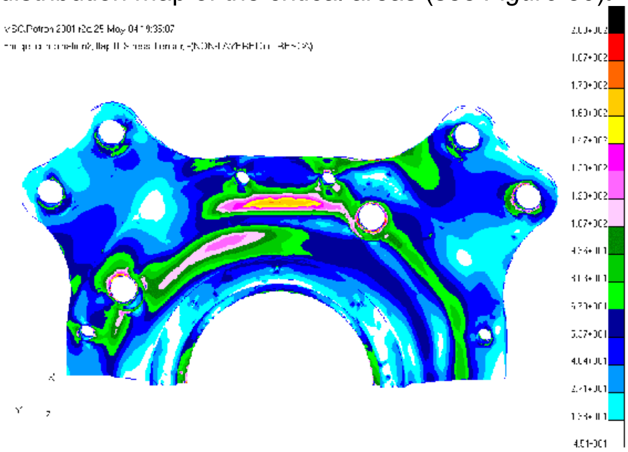

Figure 30: stress distribution map of hub-spring

Yoke

The hub includes a hollowed glass-fibre yoke, made of stacked pre-preg with epoxy resin plies. The yoke is large and thin with flap-wise flexible zones to accommodate static deflections induced by thrust while providing stiff-in-plane properties. Its central area provides room for the installation of the constant velocity joint. On the yoke are installed the elastomeric pitch bearings to transmit centrifugal and shears forces, and the hub-spring members to transmit in plane and thrust loads.

The yoke was selected for evaluation of alternative manufacturing techniques. With the baseline process for the yoke (press curing) the dimensional accuracy of the cured products is within the tolerances, but the void content of the laminates is rather high. Therefore an improved press process with application of vacuum and controlled flow under pressure was selected for further development

The development focussed on the improvement of laminate quality by lowering the exothermal peak temperature and increasing resin flow. First additional Differential Scanning Calorimetry (DSC) tests are performed. The DSC results are used to obtain a reliable simulation model. This simulation model is used to compare and verify the intended cure cycle and the thermal phenomenon of the system (thermal peaks, cooling ramps) with some meaningful autoclave experiments. In particular, products of 26 mm, 40 mm, and 60 mm have been considered. One of the final results on the simulations of autoclave cycles is shown in *Figure* 31., comparing the simulated core temperatures with the experimental ones.

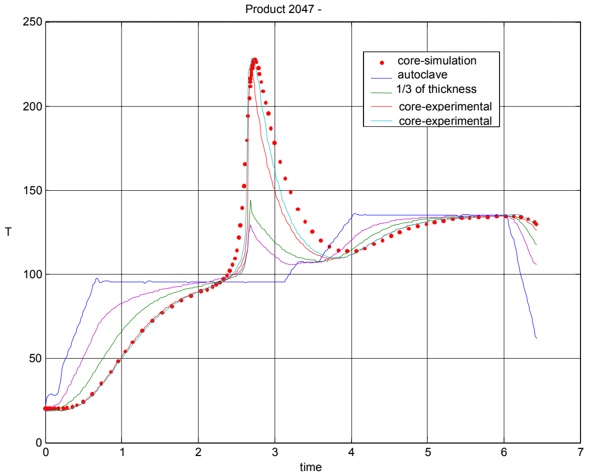

Figure 31: Comparison between autoclave tests results and simulation results

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[2] PATRAN is a trademark registered by MSC Software

[3] NASTRAN is a trademark registered by MSC Software

Additional simulations and manufacturing tests have resulted in significantly better laminate quality. Three and four point bending tests on specimens made with the new process showed improved properties and less crack growth.

Elastomeric components

Dart rotor hub technology calls for numerous and sophisticated elastomeric laminated parts. Six designs of twenty-two elastomeric components will be present in this hub.

The design life is 3000 hours based on preliminary loads.

Elastomeric elements development guidelines

Thin-layered elastomeric bearings consist of alternating layers of elastomer and metal shims bonded with the inner and outer metal housing. This design principle allows the development of elastomeric bearings with strong direction-dependent stiffness, that means high compression at simultaneous low shear stiffness. The variation of layer number, layer thickness and shear modulus distribution allows a high degree of adaptability on stiffness, space and life-time. To fulfil the requirements on high fatigue life, low-temperature flexibility, low self-heating and environmental resistance, a special blend of natural rubber and polybutadiene is generally selected.

Thin-layered elastomeric bearings are maintenance-free and include the capability for a damage tolerant design. Fatigue consists in a slow visual controllable abrasion of the elastomeric layers.

Specific Design Problems

- cocking influence on bearing life and pivot point displacement are reduced by use of hybrid bearings made of cylindrical and spherical parts,
- buckling requirements of C.F. pitch bearing requires a shape optimisation of metal shims,
- high internal heat build-up of gimbal bearings due to cyclic flapping requires the use of a special elastomeric blend with very low mechanical loss factor,
- a low-temperature flexibility of elastomeric bearings is necessary for cold start and flight manoeuvres at temperatures up to -50°C.

Design Methodology

Geometry and spring rates of elastomeric bearings have a significant influence on the rotor characteristics. Hence functional and strength oriented sizing of elastomeric bearings is an integral part of the rotor optimisation.

The design methodology of elastomeric bearings includes three iterative loops: pre-design, layer optimisation and optimisation by F.E.M. analysis..

The pre-design loop yields the bearing envelope. In the second loop, optimisation of the elastomer-shim package is performed. Primary design variables are here the number of elastomeric layers, shear modulus distribution and variation of layer thickness.

The final refinement is done by a finite element analysis. Results of structural analysis are stiffness, load path, bearing kinematics, coupling effects and stability. The stress/strain distribution is used for static strength analysis and lifetime calculation at multiaxial loading.

In addition a thermal FEM analysis is performed for calculation of heat balance and temperature distribution. Specific problems are the internal heat build-up behaviour at low and high environmental temperatures.

Hub-spring:

Its development requires extensive analysis due to heating, high insulation and high thermal expansion loads induced by heat generation.

The temperature distribution in the elastomer is provided in *Figure* 32:

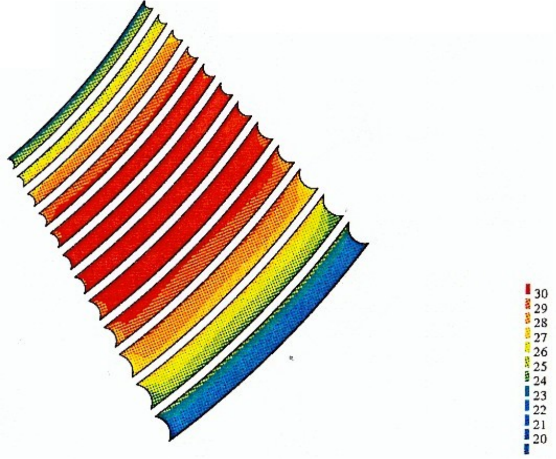

Figure 32: Hub-spring temperature plot for 11° of rotor tilt.

It can be noticed that the 11° max flapping motion will increase the hub temperature up to 30°C. To limit heat generation, a low damping elastomer will be used.

Spherical bearing for constant velocity joint mechanism :

They transmits torque between the mast and the yoke through the drive flanges and connecting pins. They accommodate cocking, torsion and axial load.

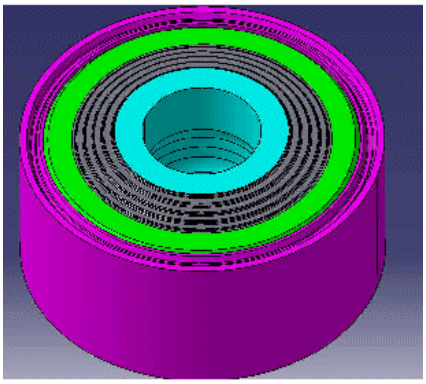

Figure 33: spherical bearing for constant velocity joint

Journal elastomeric bearings :

They enable pitch control motion without friction, transfer blade in-plane and out-of-plane shear loads and accommodate the cocking motion induced by the yoke flap-wise deflection. They are stiff enough to insure the rotor is stiff-in-plane.

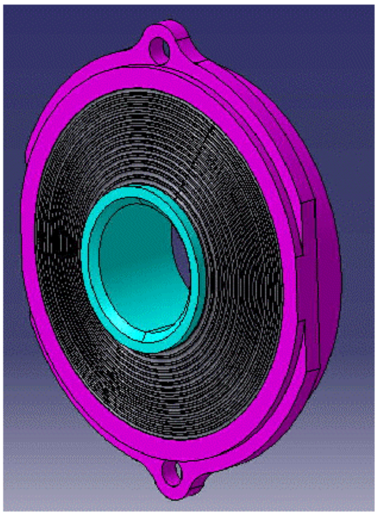

Figure 34: journal elastomeric bearing

Centrifugal force elastomeric bearings :

They enable pitch control motion, transfer blade centrifugal load, and accommodate the cocking motion induced by the yoke flap-wise deflection. Its design provides adequate buckling stability margins.

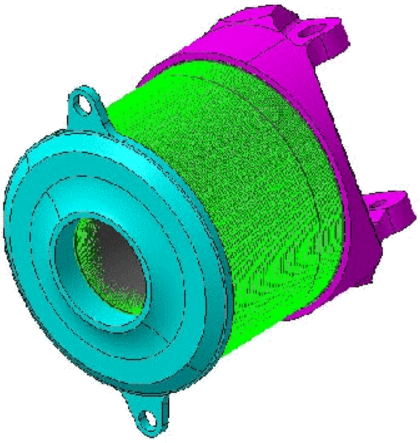

Figure 35: inner C.F. bearing

The CF bearings are highly laminated parts with optimised laminated configuration, requiring innovative manufacturing process. (undulated metallic shims)

Buckling analysis :

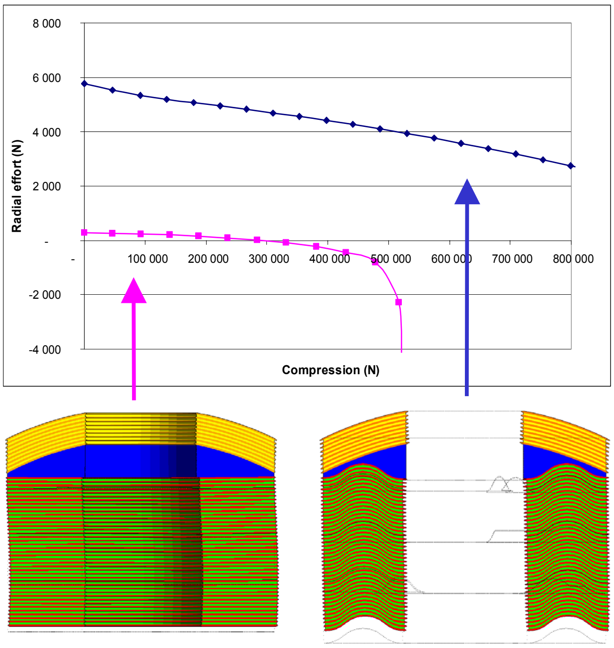

Figure 36: inner C.F. bearing buckling behaviour

The increase of compression with the same radial perturbation (1mm) generates buckling on flat laminated bearing at 450 KN. The use of undulated shims for the laminated bearing increased the radial stiffness and increased the C.F. load buckling limit (see *Figure* 36).
Few spherical layers accommodate the cocking motion without damaging the other layers.

For C.F. and pitch bearing, a low stiffening ratio at cold temperature elastomer will be used

Conclusion

As DART is entering into the manufacturing phase, it has been shown that a 4-bladed homokinetic, stiff-in-plane hub for a tilt-rotor is feasible.

Extensive loads and dynamics analyses supported the hub design by providing sizing cases, loads for substantiation, and dynamics requirements to be followed. Sensitivity analyses have helped refine the sub-system specifications.

The loads activity started with deep cross-correlation cases and the definition of the loads computation philosophy and ended with the production of limit and fatigue load cases.

The dynamics investigations provided the beam equivalent models used for the aeromechanics investigations. Both single load path and dual load path models were built. Investigations included isolated rotor dynamics and whirl-flutter studies.

The design activity led to the definition of innovative concepts and more particularly those of the homokinetic drive system and the pitch control system.

The homokinetic drive system design was driven by the requirement of a compact and symmetric (of order 4) system.

The pitch control system design, with its innovative layout of quasi-horizontal rods, was imagined to achieve the requirement of low pitch-gimbal coupling for a 4-bladed rotor.

Extensive studies were also carried in the design of the elastomeric components because of the severe constraints in terms of temperature range, loads, self-heating and buckling behaviour.

Alternative manufacturing techniques were defined to improve the quality of thick glass-fibre components. Application to the yoke manufacturing should provide a higher reliability and safe life.

In addition to the present hub design, testing and manufacturing activities, optimisation of blade design and structure have shown promising results.

The main achievements of the DART program will be used to prepare the next call for the 6th framework programme partially funded by the European Commission.

Consortium

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