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APPLICATION OF MECANO MULTI BODY FEM TOOL TO TILTROTOR MECHANISM ANALYSIS

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Abstract

This paper presents an application of the SAMCEF MECANO multi-body F.E.M tool developed by SAMTECH and used at EUROCOPTER to analyze the behaviour of a tilt-rotor driving mechanism.

Along with 8 other European partners, the EUROCOPTER group is developing an innovative 4-bladed tilt-rotor hub in the framework of the DART program. SAMTECH has been for many years a partner to EUROCOPTER in developing and providing support for efficient F.E.M. solutions for the simulation of mechanisms, the analysis of structures with linear or non-linear materials, the coupled simulation of a whole mechanical system containing mechanisms and non-linear structures in the same problem.

The DART tilt-rotor project is one of the 6 Critical Technology Projects partly funded by the European Commission that are related to the TILT-ROTOR. It is oriented towards the design and manufacturing of a full-scale rotor hub for an advanced European Tilt-Rotor configuration called ERICA (Enhanced Rotorcraft Innovative Concept Achievement). Details on the program can be found on reference [21].

Compared to a helicopter, the tilt-rotor features enhanced operational capabilities (circa double the speed and range) and better economics, while requiring only a fraction of the ground infrastructure necessary to a fixed-wing aircraft to take-off and land.

The paper first presents the overall DART hub idealization, derived from an equivalent beam model, used for aero elastic investigations. It includes beam elements, hinges, rigid and general stiffness elements.

The aim of this first model is to correctly load the inner mechanism, and in particular the constant velocity joint. This joint features 3 flanges, 4 drive links and connecting pins. Its aim is to transmit high torque with limited torque oscillations for large flapping angles.

The paper investigates in detail the behaviour and loads sharing of the constant speed driving mechanism.

For comparison, the paper also investigates the behaviour of the DART hub with an ideal equivalent constant velocity joint.

And finally, the paper provides a simplified method to derive the constant velocity joint inner loads from external aerodynamic loadings, without resorting to a complete multi-body analysis.

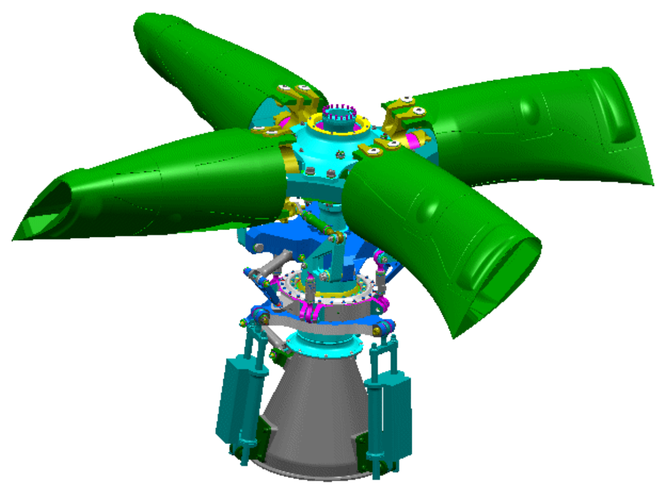

Figure 1: The DART rotor

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. Theses projects contributions will be used for the European Integrated project NICE TRIP.

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These projects are respectively:

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

The DART rotor hub design follows the guidelines of the ERICA concept which provided a general hub specification in terms of rotor characteristics.

Among the challenges in the design of a 4-bladed gimballed rotor, one can cite the design of a constant velocity joint compatible with the rotor architecture.

Early in the DART program, aero elastic codes, used by the partners, have been upgraded to enable the loads and dynamics assessment of gimballed, homokinetic rotors. This was done before the hub architecture had been chosen, and more particularly the constant velocity joint.

As a consequence, the partners implemented a kind of universal constant velocity joint, ignoring the peculiarities of the system that had still to be developed.

These upgraded codes have been successful in providing the loads that have been used to size the hub and helped refine the dynamics specifications.

Now that the DART hub architecture has been chosen, and its characteristics known, it is important to analyse the interaction of the system with the hub and finally assess the validity of the implemented constant velocity joint, with the loads provided by the aero elastic tools.

Rotor characteristics

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

Aero elastic codes are usually very refined in terms of aerodynamics and dynamics. They are however often limited in terms of structural representation and require as input, a simplification of the mechanism.

When using these codes, the first step is to derive an equivalent model, called beam equivalent model. The reference model of the DART hub 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.

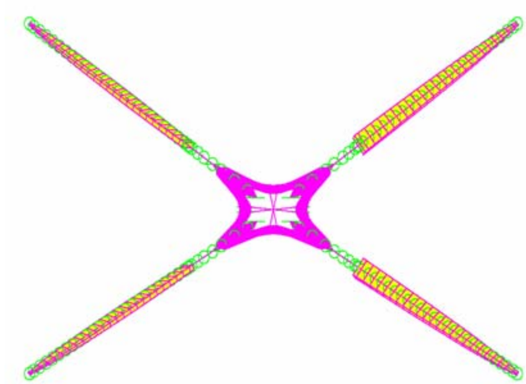

Figure 2: DART rotor Finite Element model

This model was used to compute rotor modes in vacuum for different pitch and rotor speed configurations. The beam properties were tuned to obtain close eigen-modes frequencies and shapes.

It would have been possible, although less practical, to merge the detailed structural model with the constant velocity joint model. We preferred instead to build a structural model made of beams whose characteristics are derived from the beam equivalent model. The comparison between the ideal implementation of the constant velocity joint and the practical one is then possible. Any difference between the two models will be attributed exclusively to the different Constant Velocity Joint implementation.

Both a single load path model (see Figure 3) and a dual load path model were developed for aero elastic investigations. Only the single load path model has been evaluated with the constant velocity joint mechanism.

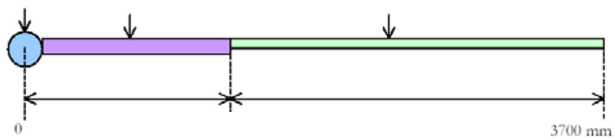

Figure 3: single load path model

Global F.E.Model

The global Finite Element Model (Figure 4) is made of a mast which drives the rotor, a spherical joint with an elastic restraint to represent the hub spring, and several beams and hinges whose characteristics come from the equivalent single load path beam equivalent model. All 4 blades are modelled.

For practical reasons, the loads are introduced after the last hinge of each blade. The aerodynamic and inertia forces of the part of the hub which is located before the last virtual hinge are thus neglected.

Loads are applied after the pitch hinges with Fourier decomposition up to 4/REV. This truncation seems reasonable considering the fact that computed loads at 5/REV are very small, that the DART hub is 4-bladed hub, and that we are investigating the peculiarities of a driving mechanism which has a symmetry of the 4^{th} order.

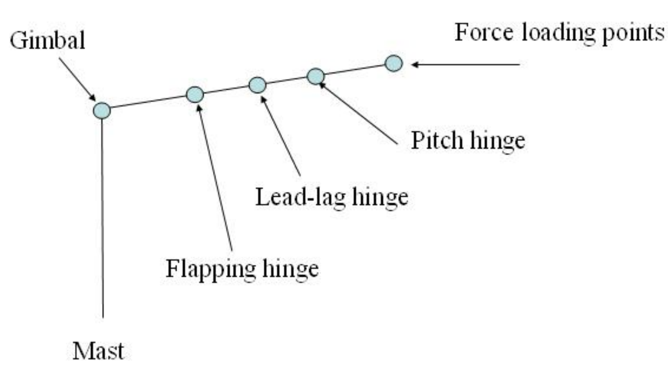

Figure 4: global F.E.Model

The global model is first evaluated with a kind of universal constant velocity joint. This model is implemented by imposing equal velocities of the mast and hub.

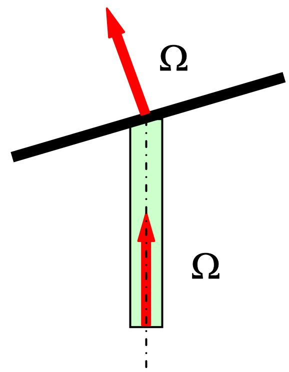

Figure 5: equal velocities

The global model is then evaluated with the actual idealisation of the DART constant velocity joint.

Design

One of the most important features retained for the DART rotor, was the constant velocity joint. Its peculiarity is to reduce blade and drive train 2/REV loads induced by the tilting of the hub.

Constant velocity joint

The constant velocity joint of the DART hub was devised with considering that:

- An inner constant velocity joint is preferable to an outer joint 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.

Without any other mechanism, such a system would have redundant and non compatible links between the mast and the hub.

To accommodate the 2/REV opposite rotational motions of adjacent links (see Figure 6) that occur when the hub is tilted, a differential is introduced (see Figure 7).

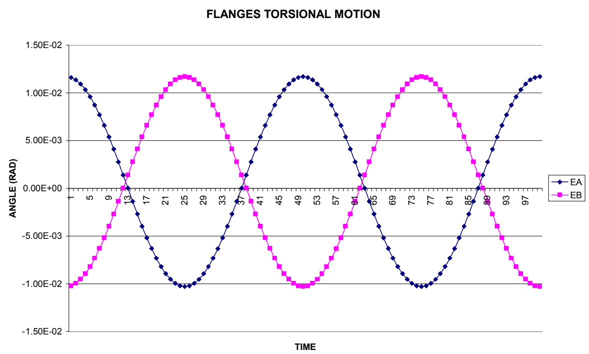

Figure 6: flanges motions for a tilted hub

This system was retained for the following reasons. 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 driven flanges, and their 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.

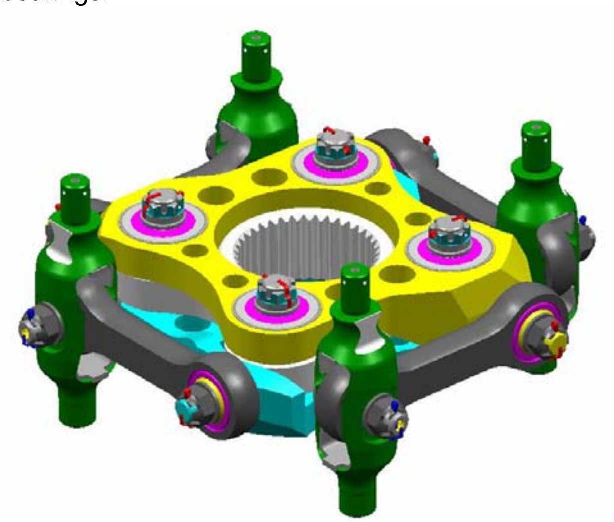

Figure 7: differential system assembly

Differential F.E.M.

The differential Finite Element Model was developed considering stiff flanges, connecting pins, and drive links. The elastomeric bearings are idealized as stiffness elements. The drive link rod ends are idealised on one end as spherical joints, and on the other end, as Cardano couplings. The choice of such a coupling is not fundamental, but it is important to avoid free motions inside the system.

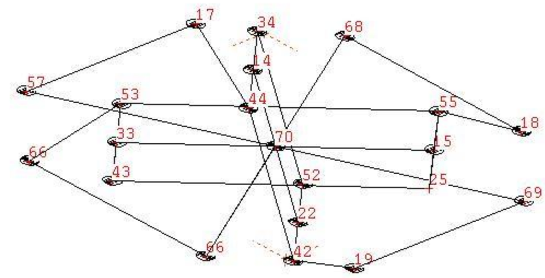

Figure 8: the differential F.E.Model

Simulation with the Global F.E.M. and differential

The simulation of the global F.E.M. with the differential is used for comparison with both the aero elastic tools, and with the global F.E.M. with a universal constant velocity joint.

In the aero elastic code, the equivalent elastic restraint at the hub centre considers both the contribution of the hub-spring and the contribution of the differential. In this model, the equivalent elastic restraint provided by the differential has to be subtracted.

The hub tilt, the hinges moments, both static and dynamic, the mast reaction forces and moments can also be compared to verify the correct implementation of the beam equivalent model.

The global F.E.M. and differential CVJ

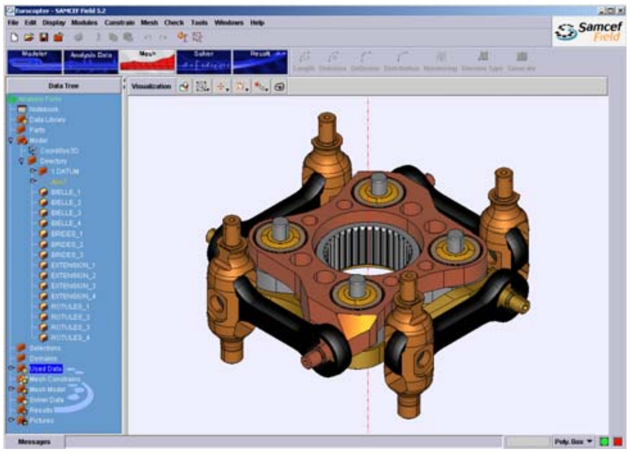

Figure 9: Importation of CAD in FEM GUI

From the differential CAD definition, a F.E.M. model is defined. In this model all components are beam elements assumed rigid and local stiffness elements or joints are introduced to describe all assemblies.

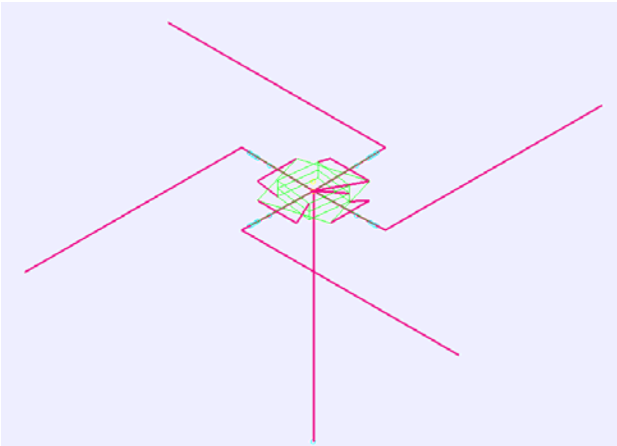

Figure 10: mesh used for global FEM simulations

Loads considered

The loads considered are the loads computed by the HOST aero elastic code for a limit load case. All 4 blades are loaded by the static and harmonic, up to 4/REV, loads. Since the loads are expressed in the blades principal axis, the pitch motion, collective and cyclic, is imposed.

Simulation with the Global F.E.M. and universal CVJ

The simulation of the global F.E.M. with the universal constant velocity joint enables direct comparison with the aero elastic tools.

The hub tilt, the hinges moments, both static and dynamic, the mast reaction forces and moments can be compared to verify the correct implementation of the beam equivalent model.

The global F.E.M. and universal CVJ

This model is similar to the first one except that the differential is made inactive by removing the 2 pairs of links. To get an equivalent universal Constant Velocity Joint, the hub-spring stiffness is corrected to take into account the homokinetic drive system restoring moments. And finally, the kinematical constraint of constant velocity is translated in some applied torque. This is detailed in the loads paragraph.

Loads considered

Likewise the global model with differential, the loads considered are the loads computed by the HOST aero elastic code for a limit load case. All 4 blades are loaded by the static and harmonic, up to 4/REV, loads. Since the loads are expressed in the blades principal axis, the pitch motion, collective and cyclic, is imposed.

In addition to these loads, a condition of equal velocity between the mast and the hub is specified. It induces a condition of torque equality.

Comparison of both models results

The Model with a universal CVJ is considered as a reference and the homokinetic behaviour of the system with a differential CVJ is validated by comparing some rotor kinematical properties.

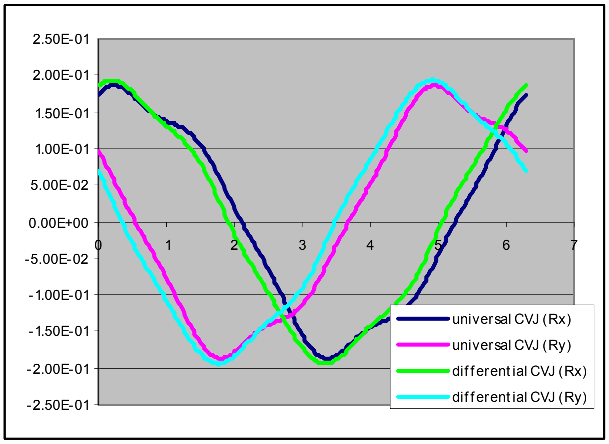

Figure 11: gimbal tilting

Figure 11 compares the gimbal tilting around two orthogonal directions perpendicular to the rotor axis for the two implementations of constant velocity joints. Results are very similar. If a Fourier transformation is applied to above signals, ones can measure influence of all harmonics. Next table gives the Fourier coefficients obtained for the signal of the differential CVJ model; differences with the reference model are also provided.

	A1	A2	A3	A4	A5
Value (rad)	1.8e-1	4.3e-4	1.4e-2	7.5e-5	8.9e-3
deviation	3.5%	13%	36%	36%	15%

Table 1: Gimbal tilt harmonics for the differential model

The two models provide very similar 1/REV tilt motions and negligible 2/REV contributions, which is a hint of a correct constant velocity joint implementation for both models.
The discrepancies between the 3/REV contributions are a hint that the differential constant velocity joint is not perfect and generates 4/REV wobbling motions in the fixed reference frame. This effect is however very small since the discrepancy is only 13% of an amplitude which is less than 1 tenth of the 1/REV amplitude.

Derivations of inner loads

The derivation of the differential inner loads is a rather tedious exercise for the following reasons:

- the motions amplitudes are rather high and linear approximations are not valid
- some loadings are induced by the isolated differential kinematics while others are partial reactions of hub loads, in combination with the hub spring
- some loadings are roughly proportional to the product of external forces and tilt angles polynomials

A complete and detailed investigation of the differential inner loads would be extremely difficult for the previous reasons. This is why it was decided to focus our analysis on the most relevant loads characteristics.

The easiest part of the loads derivation task was the computation of loads induced by the hub kinematics. It was possible to derive the inner loads for the following cases:

- hub tilt angle
- hub vertical displacement
- hub in-plane displacement

The loads and displacements are computed for increased imposed displacement amplitudes and the best polynomial fit is retained as approximation of the load or displacement computed.

Other loads are expected to be proportional to external forces and vary according to other polynomial laws of other parameters, such as tilt angle or in-plane motion. For these cases, torque or thrust is imposed and several computations are performed with increased values of the parameter considered.

For these loading cases, the analysis of reactions at the hub centre provides an assessment of the differential equivalent stiffness, which can be compared to the hub-spring stiffness. The external forces will then be shared according to the stiffness ratio: differential stiffness divided by total stiffness.

The second phase of the inner loads derivation consists in computing the reactions due to external forces, torque, thrust, in-plane loads. We should mention that these external forces have a static and harmonic components. For harmonic components, the phase is important to have a correct combination of all loads.

The final inner loads are obtained with the combination of the previous computed loads. This approximation is then tested for the external loads and motions of a particular flight condition.

As an example, we will provide the derivation of the drive link loads.

Kinematics loads

The kinematics loads are due to the elastomeric bearings stiffness. The torsion and cocking of these bearings is proportional to the flanges rotation. One can expect these loads to be proportional to the square of tilt angle.

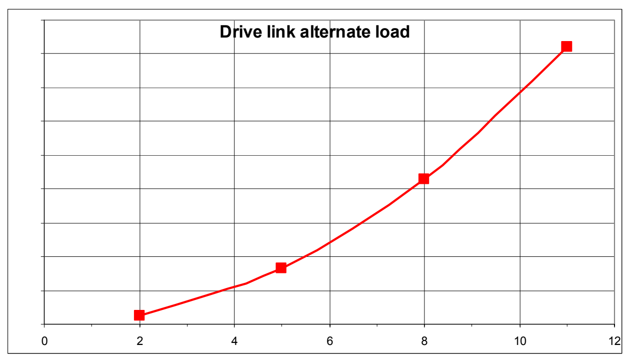

Figure 12: kinematics loads

Torque reaction

This is the main function of the differential. The equal sharing of torque between the two flanges is insured by the differential connecting pins. The equal sharing of torque loads between the drive links is another feature of the system.

This can be computed easily considering the drive links lever arms. A more refined calculation involves computing the differential torsional stiffness and a torque sharing with the hub-spring.

Both static torque and alternate (4/REV) torque modulation is transmitted to the drive links.

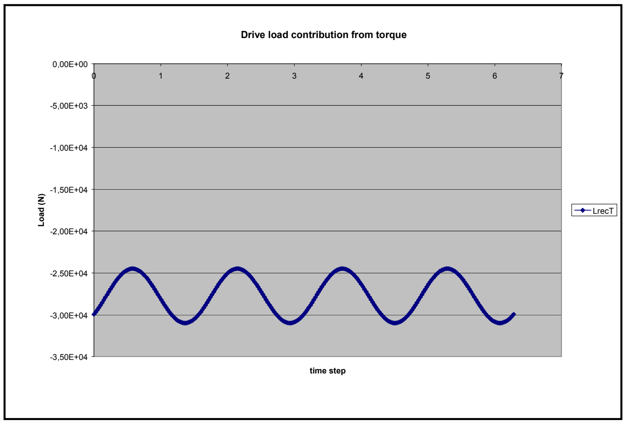

Figure 13: drive link loads contribution from torque

In-plane loads reaction

The differential has an equivalent in-plane stiffness which reacts partially the hub in-plane loads.

The reacted in-plane loads are then shared between the 4 drive links. Considering the in-plane loads are mainly 1/REV dynamic excitations, the drive link loads will also have a 1/REV component.

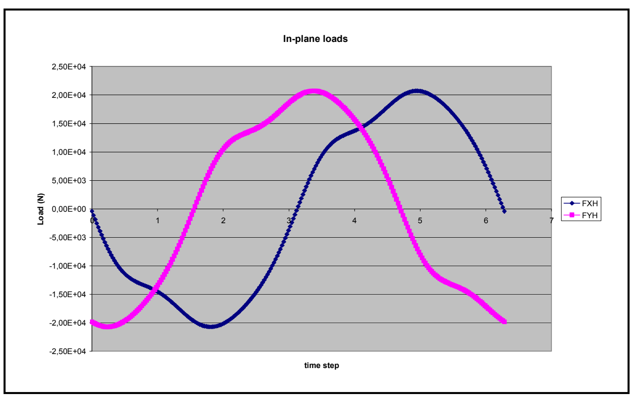

Figure 14: Hub in-plane loads

Vertical loads reaction

The differential provides an equivalent vertical stiffness when the system is loaded by torque. The system reacts partly the vertical hub loads in combination with the hub-spring.

The main impact of hub vertical loads on the drive links is provided by the thrust, which increases the drive links static loads.

Combination of loads

The F.E. model gives direct access to internal loads in any component. Figure 15 shows the time evolution of the lift force measured inside the gimbal and the normal force in one of the four links.

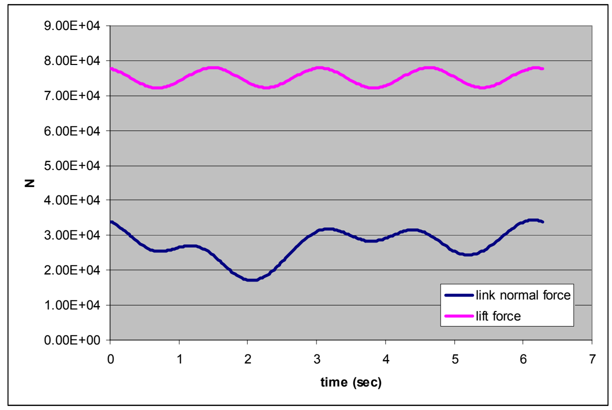

Figure 15: internal loads in links and gimbal

The Fourier transformation, Figure 16, shows, as expected, that the lift is a combination of a static load and the 4th harmonic; for the links, only harmonic 3 is negligible.

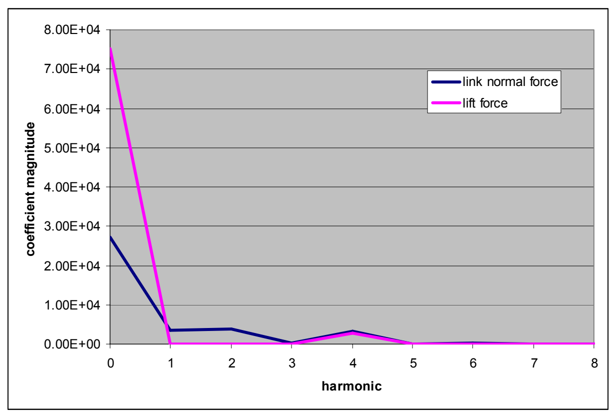

Figure 16: Fourier transformation of drive link load

The combination of loads consists of the addition of the various contributions. The major contributors are the torque reaction, the in-plane loads partial reaction, and the kinematics loads. Limiting the contribution to these factors was sufficient to get a very good estimation of the drive link inner loads.

The following formula is used:

$$F = A * Torque + B * Fx + C * Fy + D * \beta^2$$

The coefficients are either physical characteristics or identified parameters.

Figure 17 provides the comparison of derived drive link load with the computed one.

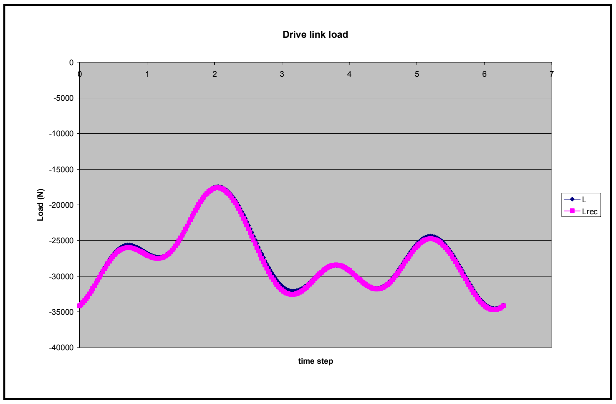

Figure 17: comparison computed/derived link load

One can notice a very good correlation between the two methods.

Conclusions

The implementation of the differential in the global DART rotor finite element model was successful. SAMCEF Mecano proved to be an efficient tool for multi-body analysis. Motions, reaction forces, inner loads can be extracted easily. Fourier analysis of extracted parameters are also straightforward.

The comparison of the global model with the DART constant velocity joint and the global model with the universal constant velocity joint proved the DART system behaves very similarly to a perfect and ideal constant velocity joint. However, the DART Constant Velocity Joint is not perfectly homokinetic and generates some wobbling motion at 3/REV in the rotating frame.

A methodology was proposed to derive inner loads in a simplified but more efficient manner. This avoids a complete simulation for each flight condition considered. From the more detailed and complete formula, an approximate formula for inner loads extraction was derived. It proved to be quite precise.

DART consortium

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EUROCOPTER
EUROCOPTER DEUTSCHLAND
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SPASA
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Acknowledgements

The authors would like to express their gratitude and esteem to the partners involved in the DART program for their very fruitful contribution and co-operative and open-minded attitude.

Gratitude is also expressed to the European Commission who has sponsored this program and encouraged this co-operation among European helicopter manufacturers, suppliers and design and research centres.

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