OVERVIEW OF THE 11-TON HELICOPTER DEMONSTRATOR DYNAMICS VALIDATION PROGRAM

Laurent THEVENOT
Dynamics Engineer
Eurocopter, Marignane, France

Abstract

The 11-ton Helicopter Demonstrator developed by EUROCOPTER is derived from the Super Puma family. It is an upgrade of the AS332L2 version, mainly based on a new five-blade main rotor, new TURBOMECA Makila 2A engines and a new avionics suite, including a new auto-pilot.

This paper gives an overview of the dynamics validation program which was applied during the 11-ton Helicopter Demonstrator development, from the design stage up to the flight tests.

The first point concerns the dynamic adaptation and the aeroelastic stability of the main rotor and the tail rotor. The identification of the main rotor modes at the whirl tower is presented with a comparison between theoretical values and measurements.
Then, the stability in ground resonance and in flight resonance is approached.

The second point is the study of the drive train. First, the location of the dynamic chain modes is studied. The stability at low frequency is analysed by the study of the coupling between the first chain mode and the engine governing. The study is conducted in association with the engine supplier. It was performed with prototype engines installed on the 11-ton Helicopter Demonstrator. The flights confirmed the good stability of the drive train.

The third point is the vibratory level of the aircraft. A shake test of the helicopter was carried out. The purpose of the test was to identify the frequencies and the modal shapes of the fuselage in laboratory. The fuselage natural frequencies and modes, as identified during the shake test, have been correlated with the calculation which need some adjustments.

On the four-blade AS332L2, the anti-vibration systems are the flexible-mounting plate and the blade pendulum absorbers.
For the five-blade 11-ton Helicopter Demonstrator, several systems were considered to cancel vibrations: flexible-mounting plate, blade pendulum absorbers, active resonators.
Finally, this paper gives the solution selected after the flights tests.

1 Introduction

The 11-ton Helicopter Demonstrator is the latest evolution of the Super Puma / Cougar family. If the relationship between the 11-ton Helicopter Demonstrator and its father helicopter – the AS332L2 Super Puma – is obvious due to their common appearance, the new Demonstrator concentrates the most recent technologies available in Eurocopter, embodied in state of the art new designed components and equipment.

These components and equipment are mainly:

- a new five-blade main rotor hub
- new high performance main rotor blades
- an upgraded Main Gear-box with increased power ratings and dry run capabilities
- new TURBOMECA Makila 2A engines with dual channel FADEC
- new cockpit avionics suite
- a new auto-pilot of the EC135 / EC145 / EC155 family

The program was launched in 1999 and the Demonstrator flew in December 2000 (figure 1).

Photo X. - Eurocopter

Figure 1
11-ton Helicopter Demonstrator in flight

The main challenge for the Eurocopter Dynamics Team was to meet the stringent design requirements applicable for stability, oscillatory loads and vibrations in every flying envelope and for different load configurations. Particular attention was paid to vibration reduction. This paper reviews the methodology used for the 11-ton Helicopter Demonstrator development as regards:

 © EUROCOPTER 2002. All rights reserved.

- Main and tail rotor dynamics
- Drive train system dynamics
- Vibration control
- Flights tests

2 Main rotor

As for the AS333MK2, the 11-ton Helicopter Demonstrator main rotor system is designed as "soft in plane" (figure 2).

Photo X. - Eurocopter

11-ton Helicopter Demonstrator main rotor

Figure 2

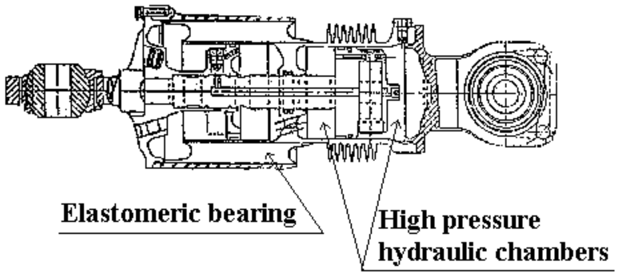
Simple design, low price, reliability and easy maintenance dictated the soft in plane concept choice. The spherical elastomeric bearings are retained from the AS332MK2.

Lead-lag dampers are fitted to counter aeromechanical rotor/fuselage instabilities because it is difficult for the designer to avoid ground and flight resonance.
The hydro-elastic damper technology was used for the 11-ton Helicopter Demonstrator, as for the AS332 (figure 3a and 3b).

Photo X. - Eurocopter

Hydroelastic damper

Figure 3a



Hydroelastic damper

Figure 3b

Hydro-elastic dampers combining high damping and low stiffness are used.
For the 11-ton Helicopter Demonstrator, the stiffness of the elastic bearing is increased.

Whirl Tower Tests

The complete rotor was tested on the whirl tower as shown in figure 4.

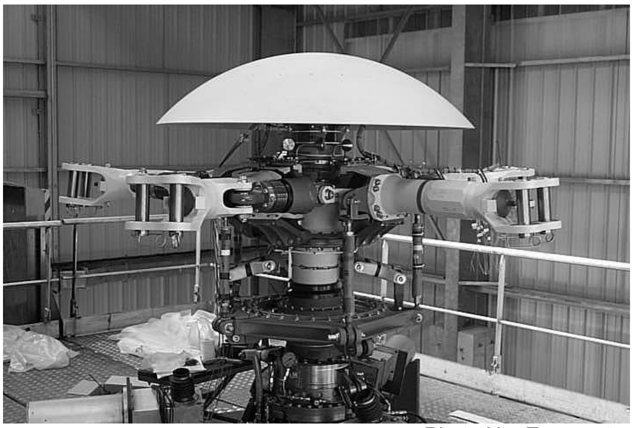


Photo X. - Eurocopter

Figure 4

Main rotor at the whirl tower

The identification of the first four flap frequencies, the first two lead-lag frequencies and the first torsion frequency was emphasised from a dynamic standpoint.

A hydraulic actuator on the whirl tower excited rotor modes. The tests were concentrated on modes that influence flight dynamics, aeromechanics and vibrations.

To attain the low stress and vibration objective, the blades must be tuned, with a separation as large as possible between natural blade modes and the nearest rotational speed harmonics. Test data (rotating system) are in the frequency diagram (figure 5). The theoretical frequency curves are drawn from the advanced HELICOPTER OVERALL SIMULATION TOOL code. The comparison between

© EUROCOPTER 2002. All rights reserved.

calculation and measurement points shows a fairly good agreement (figure 5).

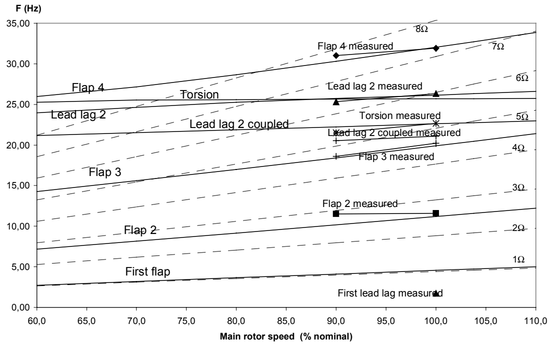


Figure 5
Frequency diagram of the main rotor
Measured frequencies compared with the calculated frequencies

The second lead lag mode was measured close to the 6/rev of the main rotor, and the collective lead lag mode close to the 5/rev.

Tuning of the 2nd lead lag mode was investigated during the whirl tower tests with addition of a tuning mass at 40% blade radius. The theoretical calculations were validated by the test data and the results are shown in figure 6.

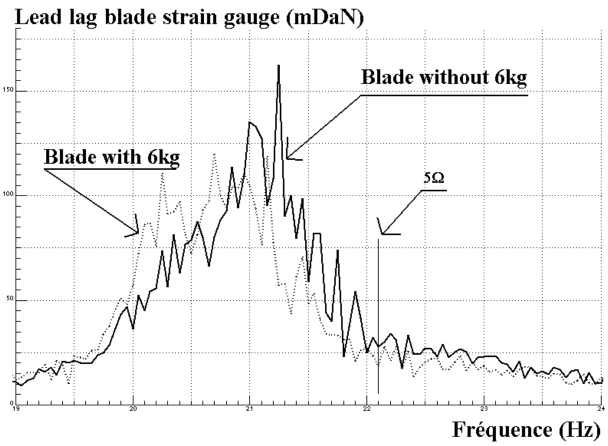


Figure 6
11-ton Helicopter Demonstrator whirl tower test
Influence of tuning mass on blade's dynamics

The frequency and damping behaviour of the 1st lead lag mode at different pitch control settings was recorded in detail for ground resonance and drive train considerations. Damping was evaluated by recording the amplification during frequency sweep excitation.

The frequency measured for the first regressive lead lag mode is 1.75Hz.

Ground resonance stability

The ground resonance is the result of a coupling between a body mode and the first drag mode of the rotor, in fixed system. The body modes are generated by the structure on the landing gear. The lead-lag motion of the blade then induces loads on the hub that are generated as a result of a lateral and longitudinal shift in the rotor centre of gravity from the centre of rotation. These loads excite both the rotor-fuselage modes at its natural frequency, thus inducing displacements in the centre of the rotor, and the rotor at its natural frequency.

Unstable ground resonance is highly destructive and has been the cause of early prototype crashes. Obtaining satisfactory stability margins is one of the prime concerns in current helicopter design.

The component and whirl tower tests were helpful to verify and to improve the analytical rotor models.

For the 11-ton Helicopter Demonstrator, the most critical mode is the 2nd of roll at approximately 3Hz.

The 11-ton Helicopter Demonstrator stability margins were calculated with the GAHEL software (figure 7).

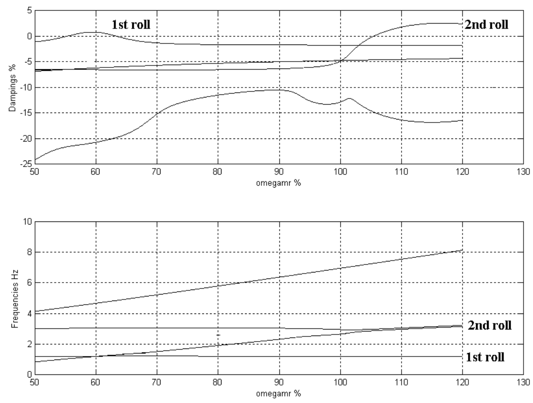


Figure 7
11-ton Helicopter Demonstrator: Stability in ground resonance

The modal damping values were evaluated in the non-rotating system with different helicopter weights. The calculated stability margin was sufficient in every configuration.

The ground resonance flight tests showed that rotor and fuselage oscillations due to cyclic excitation died down quickly when solicitation stopped (figure 8). The flight tests showed that the helicopter is not subject to ground resonance.

 © EUROCOPTER 2002. All rights reserved.

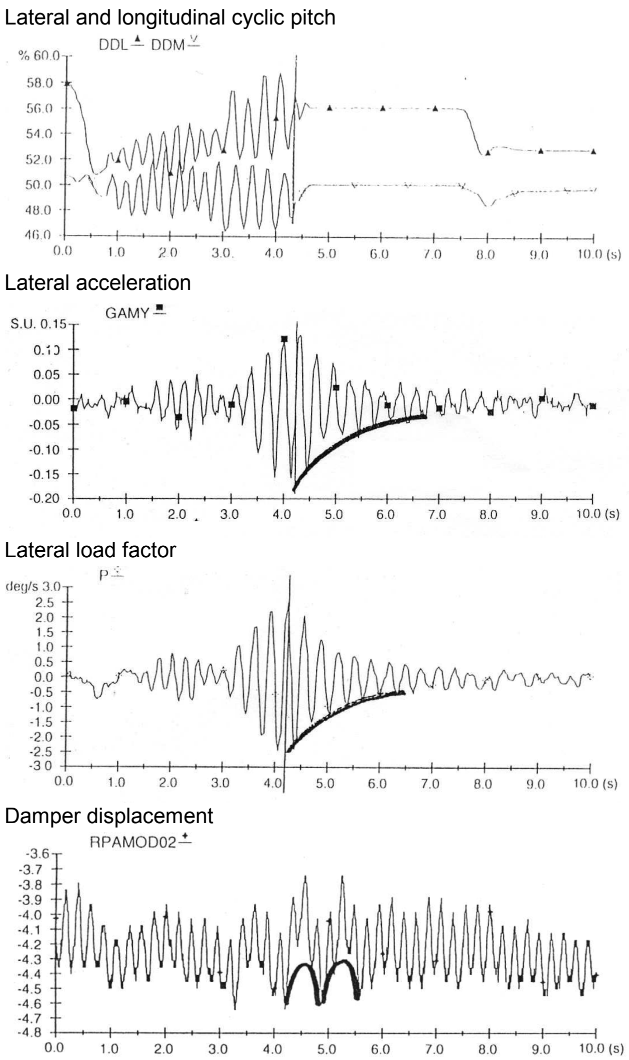


Figure 8
11-ton Helicopter Demonstrator: ground resonance flight test result

Flight resonance stability

Air resonance is similar to ground resonance and involves coupling the first lead lag, the first flap and rigid body fuselage mode.

An oscillation in roll leads to a pitch increase on the blade, inducing a response in the flap and in the lead lag (by the effect of Coriolis). The response of the blade in lead lag induces an effort in the rotor head, inducing oscillations of the fuselage in roll, closing the loop.

The air resonance appears in cases where the rotor is loaded.
Theory as well as experience on the 332MK2, NH90 and 365N4 indicates flight conditions favouring air resonance:
- Flight at high altitude
- Flight with heavy weight
- A high temperature

The phenomenon was identified by excitation of the fuselage on its roll axis from a frequency generator (sweep frequency).

The phenomenon is characterised by (figure 9):

- Oscillations in lead lag for the main rotor at the frequency of 1.8Hz approximately (first lead lag mode)
- Structural oscillations in roll at approximately 2.6Hz.

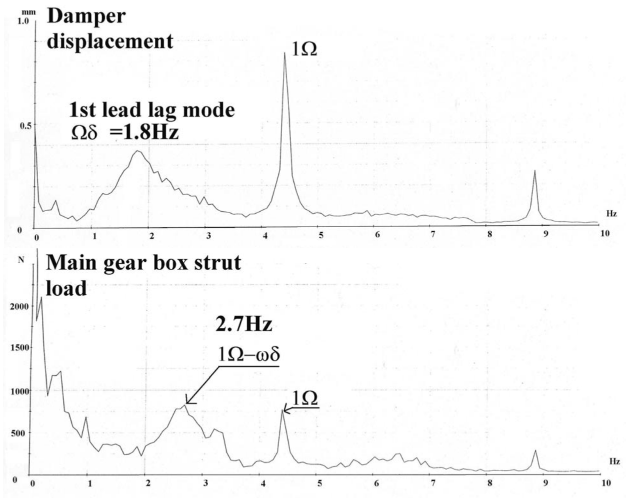


Figure 9
11-ton Helicopter Demonstrator: flight resonance flight test identification

In the flight envelope covered to date, no significant oscillation of air resonance was measured or felt by crews.

The flight resonance stability margin was obtained with hydro-elastic damper (high damping with bi-frequency solicitation).

3 Tail rotor

The articulated four blades tail-rotor is the same as for the 332MK2, but with a new blade.

To reach the low stress and vibration target, the blades must be tuned far away from resonance, with a separation as large as possible between natural blade modes and the nearest rotational speed harmonics. This design philosophy was applied to the 11-ton Helicopter Demonstrator tail rotor as shown on figure 10.

Figure 10 shows that adequate blade stiffness was provided to avoid undesirable coupling of torsion and bending modes.

 © EUROCOPTER 2002. All rights reserved.

The flights showed good rotor performance, identical to that of the 332MK2.

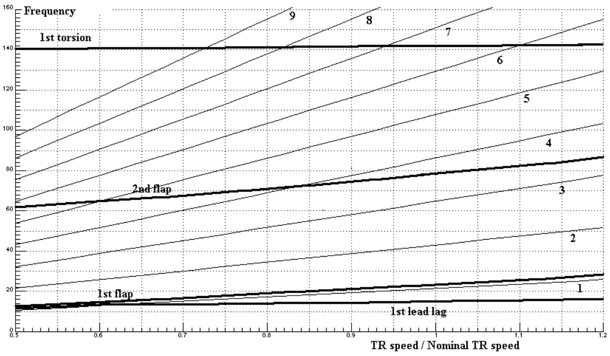


Figure 10
Frequency diagram of the tail rotor

The tail rotor is soft-in-planes and requires a lead lag damper to prevent “ground resonance” instability (coupling with the fuselage vertical bending mode). The same elastomeric dampers as used on the TIGER were selected for the Demonstrator tail rotor because of their simplicity, damage tolerance and low price. The calculated stability margin was sufficient in every configuration (figure 11).

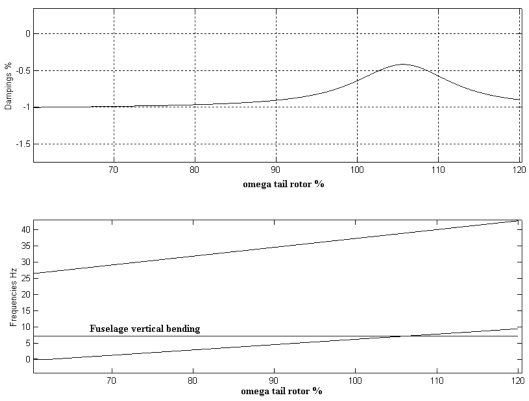


Figure 11
11-ton Helicopter Demonstrator: Tail rotor stability in “ground resonance”

4 Drive train dynamics

The helicopter drive train system is composed of rotors, engines and their fuel control laws, shafts and gear. Together these systems can generate different dynamic problems such as torque oscillations and rotor speed variations that degrade the handling qualities. The 11-ton Helicopter Demonstrator drive train dynamic analysis mainly focused on appropriate tuning of the torsion modes of the system, providing a proper separation from the 5/rev as well as the 10/rev excitation frequency. It also focused on the torsional analysis of low frequency stability in cooperation with the engine manufacturer.

The drive train torsional dynamic model is shown in figure 12. This model designed without any major simplifications, helped to analyse the torsional dynamics of the whole drive train system.

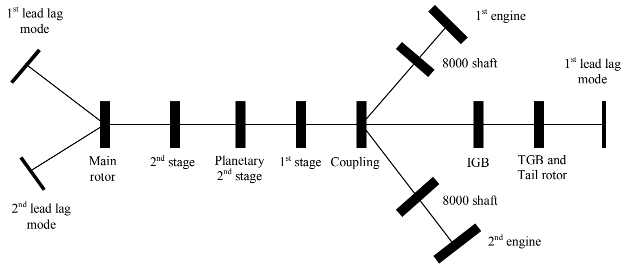


Figure 12
11-ton Helicopter Demonstrator drive train model

The first drive train mode, which is of interest for engine fuel control laws, was computed at 2.95Hz (figure 13). The second significant result derived from this analysis was the presence of the drive train mode close to 5/rev. This mode is related to the 2nd collective lead-lag mode which is reduced by the flexibility of the main rotor shaft. The frequency of this mode can be tuned by adding a weight at 40% blade radius. The results of the flight showed that it was not necessary to use the weights.

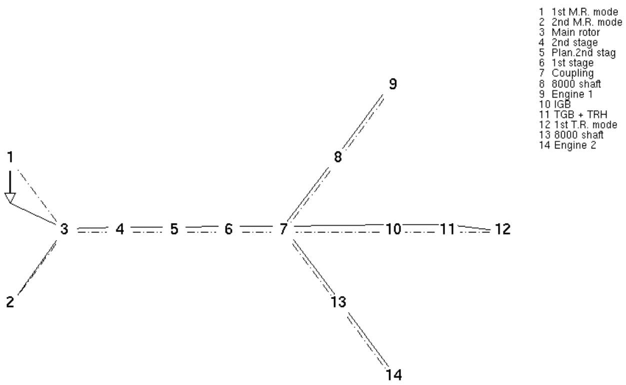


Figure 13
Drive train model
1st mode: 18.6 rad/s = 2.95 Hz

Another important aspect regarding the drive train investigation is the low frequency stability analysis which is performed with a simplified model. The non linear engine characteristics provided by Turbomeca were linearised about a steady condition. The stability margins were derived from standard open loop Bode plot.

As an example a Bode diagram applicable to the 11-ton Helicopter Demonstrator at its maximum take-off weight is presented (figure 14). The classical stability margins are respected. Flight tests confirmed that

© EUROCOPTER 2002. All rights reserved.

the stability behaviour of the drive train system was satisfactory.

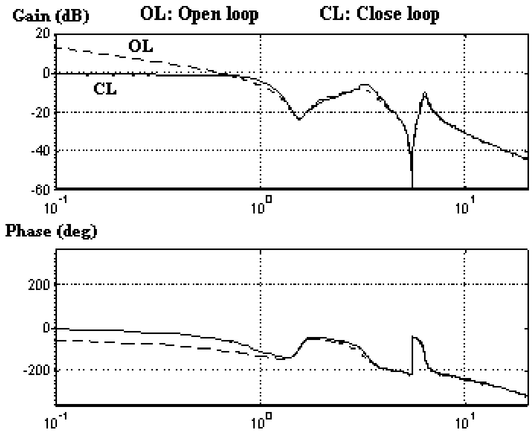


Figure 14
11-ton Helicopter Demonstrator drive train stability study

5 Vibration control

One of the most significant parameters when evaluating the success of a helicopter's design is the vibration characteristic.

The vibration objective in the 11-ton Helicopter Demonstrator specification was to obtain a 5/rev level lower than 0.2g in the flight envelop at the pilot and copilot floor.

To fulfil this ambitious goal, vibration problems were taken into consideration very early in the design process.

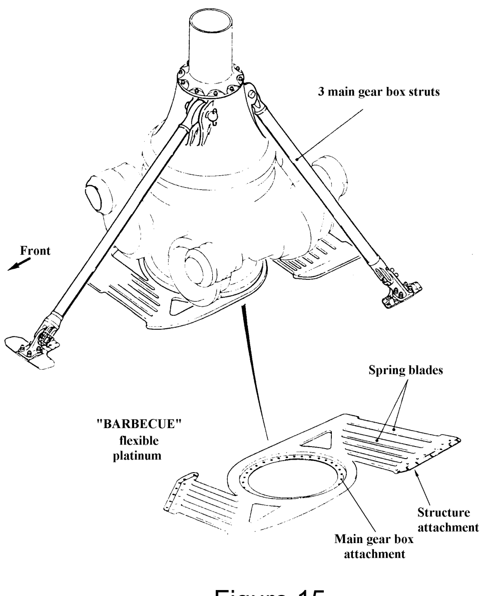


Figure 15
Flexible-mounting plate

On the four-blade AS332L2, vibration control means are the flexible-mounting plate and the blade pendulum absorbers. For the five-blade 11-ton Helicopter Demonstrator, several systems were considered:

- flexible-mounting plate (figure 15)
- blade pendulum absorbers
- active resonators

Fuselage dynamics

The development of the fuselage was supported with extensive finite element calculation.

The 11-ton Helicopter Demonstrator has the same fuselage as the 332MK2. But with the new 5 blade main rotor, the excitation frequency is now 22.1Hz (5/rev). Dynamic study of the fuselage was an obligation. A finite element model was developed according to figure 16 for detailed theoretical investigations.

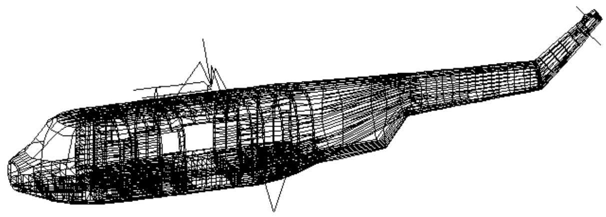


Figure 16
Finite element model

This model had approximately 16000 degrees of freedom. The fuselage transfer was minimised in the region of 5/rev. The basic optimisation parameter was the flexible-mounting plate longitudinal stiffness.

A shake test was carried out very early in the development with a whole airframe (figure 17).

Photo X. - Eurocopter

Figure 17
11-ton Helicopter Demonstrator shake test

© EUROCOPTER 2002. All rights reserved.

The helicopter was attached at the rotor head for dynamics investigations in free-free state. The connection to the supporting frame was made with a soft air spring tuned with the helicopter mass to approximately 1Hz.

With the shake-test result, a readjustment of the finite element model was realised. Figure 18 gives two examples of modal deformation.

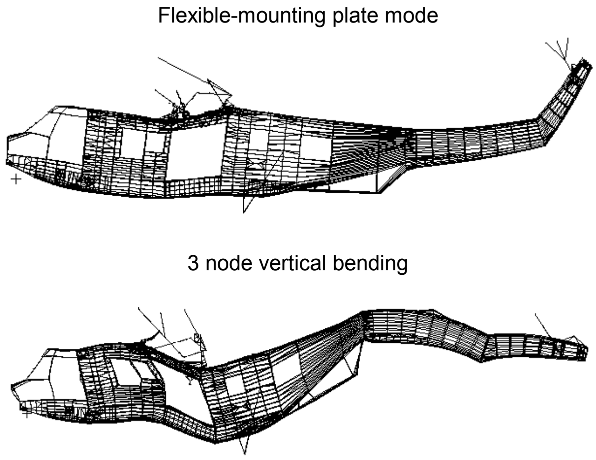


Figure 18
11-ton Helicopter Demonstrator
Examples of modal deformation
Calculus by finite element method

Active resonators

The system is constituted of a set of effort generators located in the cabin, piloted by a real-time computer, intended to minimise the vibratory level, from the response of a set of accelerometers.

The shake-test allowed the integration of the active resonators to be prepared before the first flight. The response of the cabin to the effort resonator was measured for two resonator positions, forward and aft. Then the updated finite element model was used to realise a parametric study to optimise the positions tested in flight (figure 19):

- two resonators in forward area of cabin
- two resonators in aft area of cabin

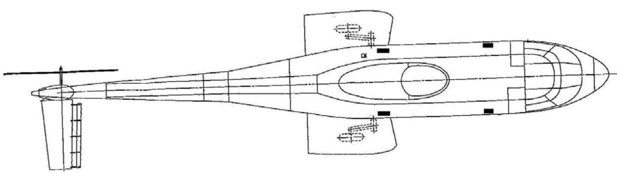


Figure 19
Resonator positions tested in flight

Flight tests

Since the first flight of the 11-ton Helicopter Demonstrator in December 2000 many aspects of helicopter performance, dynamics and control have been tested.

The low vibration level obtained with active resonators impressed the crew, in the entire flight envelope. The measurements clearly demonstrated that the vibration level is lower than 0.2g at the pilot and copilot floor, in the flight envelope (figure 20). At high speed, the vibration level is 0.1g all over the fuselage.

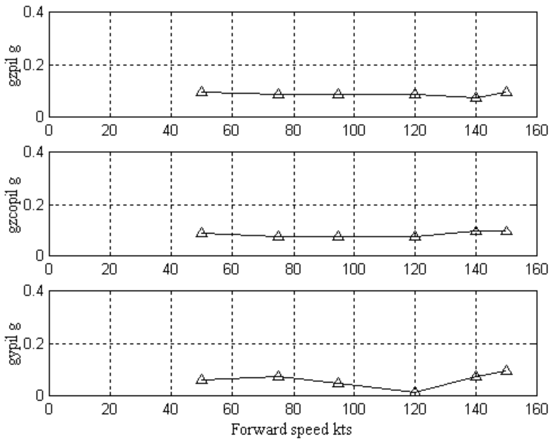


Figure 20
11-ton Helicopter Demonstrator: vibration levels with active resonator

The decision was taken to suppress blade pendulum and to install active resonators:

- one resonator in forward area of cabin
- two resonators in aft area of cabin

The retained solution allows costs, weight and maintenance to be reduced.

6 Conclusions

The dynamics validation program of the 11-ton Helicopter Demonstrator leads to the following conclusions:

- The main and tail rotor dynamics objectives were rapidly attained by intensive theoretical calculation, design provision and advanced whirl tower testing.
- The aeromechanical stability margins were adequately predicted using the whirl tower and shake test results.
- The theoretical calculations of fuselage and the shake test were beneficial for vibration control.

© EUROCOPTER 2002. All rights reserved.

- A very low vibration level at 5/rev was obtained with advanced active control technology.

The solutions developed for the demonstrator are applied to the EC225/EC725. Flight tests of the EC225 are still in progress. However, it can be already stated that works undertaken on dynamics has proved successful, because of the coherent and logic methodology applied.

7 References

Meeting Paper – GERHARD, S, and KRYSINSKI, T, "Overview of TIGER Dynamics", American Helicopter Society 48th Annual Forum, Washington, DC, June 1992.

Meeting Paper – KRYSINSKI, T, and FERULLO, D, "Overview of the EC155 Dynamics Validation Program from Design Stage Up to Certification", American Helicopter Society 55th Annual Forum, Montreal, CANADA, June 1999.

Meeting Paper – FAURY, G, "EUROCOPTER EC225/725: An Example of Risks Management", 27th European Rotorcraft Forum, Moscow, RUSSIA, May 2001.

8 Acknowledgements

The author wishes to acknowledge the contributions of the following organisations towards this program:

- The Office National d'Etude et de Recherche Aérospatiales for the technical support
- The DPAC-SPAé for the funding of research aspects

© EUROCOPTER 2002. All rights reserved.