MODIFICATION OF A FOUR BLADED MAIN ROTOR – IMPACT ON DYNAMICS AND VIBRATIONS

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Abstract

Amongst several improvements of the EC135 dynamic system the existing 4-bladed main rotor of the EC135 was modified to achieve better hot and high performance. The altered rotor features an increased diameter and blade twist. The main rotor was designed and tested on the Eurocopter EC135. This paper provides an overview of activities in dynamics and vibration related to the design changes necessary to meet improved flight conditions. It focuses on lay-out considerations, stability investigation and vibration prediction during the modification design process. Findings of first steps of industrial use of vibratory prediction using CAMRAD II and CFD-CAMRAD II coupling in the design process are presented. With the resulting concept rotor a good balancing between the performance increase and vibratory hub loads could be achieved in a very early stage of development. Furthermore the impact of the design changes on anti-vibration measures is discussed. The helicopter equipped with present and future anti-vibration technology, like AVCS, would exhibit good cabin vibration levels equivalent or better than current series EC135.

NOMENCLATURE

AEO	All Engines Operative
ARIS	Anti Resonance Isolation System
AVCS	Active Vibration Control System
CAMRAD	Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics
CFD	Computational Fluid Dynamics
FxLMS	Filtered-x-Least Mean Square
HOGE	Hover Out-of-Ground Effect
ISA	International Standard Atmosphere
MTOW	Maximum Take Off Weight
RPM	Revolutions Per Minute

1. INTRODUCTION

Continuously monitor and adapt to customer needs is key to remain a strong industry player in the light/medium weight helicopter segment. Therefore various modifications of the EC135 dynamic system including a new rotor blade were developed and tested on an EC135 [1]. This paper presents an overview of dynamic activities required to design the improved rotor and to predict possible impact on dynamics and vibration. CAMRAD II calculations with free wake models and CFD are performed. Complementary investigations of anti-vibration systems in order to control vibration level in enhanced environment are included. Finally some results of specific ground and flight tests during the development are shown as well.

2. MODIFICATIONS ON THE PROTOTYPE

The improvement of the EC135 is based on the following requests for change of the take-off weight combined with improved performance especially at hot and high conditions:

- Increase of Maximum Take-off Weight from 2950 kg to 2980 kg
- Increase of HOGE Performance by at least 100 kg at ISA, and at least 200 kg at ISA+20 conditions (limited by MTOW)

Various measures are taken to achieve these improvements mainly by changing rotor and engine parameters. The most important modifications are:

- Increasing the rotor diameter and twist distribution
- Change of engine air inlet to reduce installation losses
- Increase of AEO and OEI engine power
- Increasing rpm variation range

3. CALCULATIONS

The most important change from dynamic point of view is the modification of the main rotor. The design of a high efficient rotor with a balanced compromise between static, dynamic, fatigue and aerodynamic has always been one of the major challenges for helicopter manufacturers. The mentioned rotor change inherently initiated an extensive evaluation of the design changes on dynamics and in particular vibration. A CAMRAD II [2] model of the new main rotor was established early in the design process. The computations are used for dynamic layout, stability analysis and vibratory load prediction.

3.1. Dynamic layout

General dynamic design philosophy is to locate the rotor frequencies in a way to avoid resonances with rotor harmonics. As the basic stiffness distribution of the blade is given by the EC135 serial blade, mass tuning was the single mean to create satisfying blade frequency placing. The EC135 blade tip mass was modified in position and amount of mass. The frequency placing was monitored by calculations with the ECD in-house tool MOSES (uncoupled calculation of beams in centrifugal field) and in later stages by CAMRAD II (multi body code for helicopter applications) models.

Figure 1 shows a fan diagram for the new rotor. The figure shows characteristics for CAMRAD II and MOSES calculations as well as whirltower test results. In the CAMRAD II results a coupling between first torsion and third lead-lag modes can be observed. MOSES is not able to represent such couplings. For the other modes good agreement between the results of the two tools can be seen.

A special issue for the dynamic layout of the rotor blade is the first lead-lag mode and its appropriate damping. For the modified rotor the aim was to keep the first lead-lag natural frequency and damping in the same range than for the serial EC135 rotor.

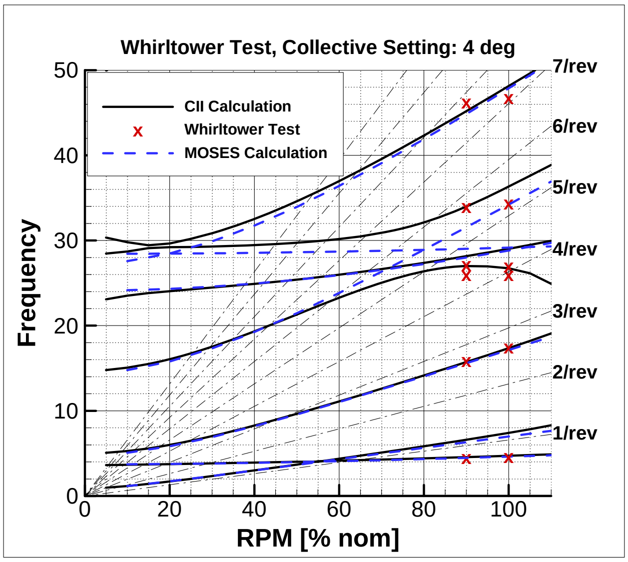

Figure 1: Fan diagram showing calculations and whirltower measurement

The same elastomeric lead-lag dampers as for the EC135 serial rotor are used. Their non-linear properties are well known and were included in the models at linearization points. The second lead-lag frequency was slightly decreased in comparison to the EC135 serial rotor to achieve better frequency placing of the second drive train mode compared to serial EC135. The rotor dynamics properties were validated by a whirltower test.

3.2. Stability

Stability considerations for ground and air resonance, rotor blade flutter and drive train oscillations were done.

3.2.1. Ground resonance

For ground resonance stability considerations the CAMRAD II model, mentioned above, was combined with modal data of the airframe on ground, derived from FE-models. The frequency and damping characteristics of the airframe's pitch and roll mode and the rotor's first regressive lead-lag mode versus main rotor speed were calculated. As the magnitudes of changes in dynamic properties of the main rotor were only small and the airframe is considered as unchanged only spot check calculations at two points of the mass versus C.G. envelope were performed before flight testing. Figure 2 shows first regressive lead-lag and airframe on ground (first roll and first pitch) frequencies versus main rotor speed and Figure 3 the according damping.

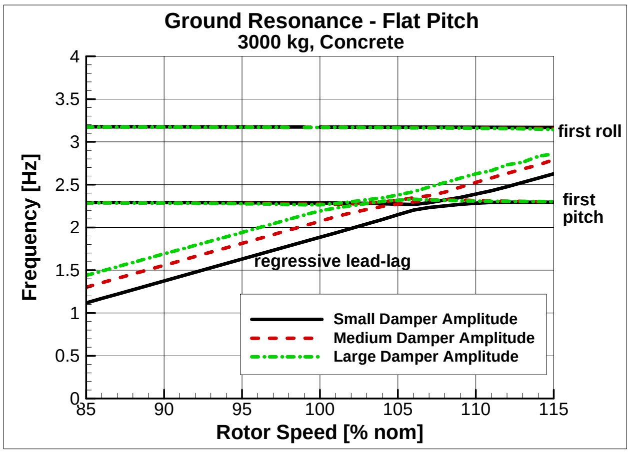

Figure 2: Ground resonance plot: Frequencies

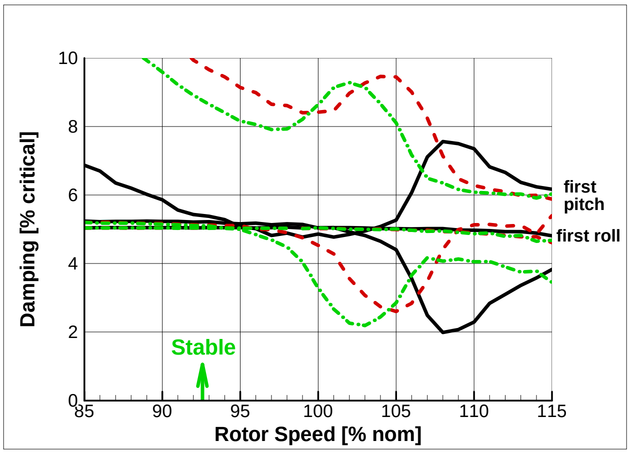

Figure 3: Ground resonance plot: Damping

The calculation was performed for flat pitch, a helicopter with 3000 kg gross mass on concrete surface and for three different lead-lag damper amplitudes to cover for the non-linear behaviour of the elastomeric lead-lag dampers. As can be seen in Figure 2 the crossing between first regressive lead-lag frequency and first pitch frequency of the airframe on ground can occur within the operational range of the helicopter. Like for the series EC135 the lead-lag dampers ensure stable behaviour in this case.

3.3. Air resonance

For air resonance stability considerations the impact of the rotor changes on main rotor natural frequency placing of the first regressive lead-lag mode and rigid body roll and pitch modes of the airframe in flight was considered. The characteristic of first regressive lead-lag frequency versus main rotor speed is slightly shifted to even more comfortable ranges compared to serial EC135. Therefore no dedicated air resonance calculations were needed.

3.3.1. Rotor blade flutter

For rotor blade flutter stability the effect of diameter and mass tuning changes on the chord wise location of the blade's centre of gravity and on the rotor blades flap (2nd and 3rd) and torsion (1st) frequencies was investigated. Table 1 lists 1st torsion, 2nd and 3rd flap frequencies, equivalent chord wise centre of gravity and control stiffness differences between serial EC135 rotor blades and the new blades. As the chord wise location and natural frequencies were nearly unchanged compared to the EC135 serial rotor no dedicated aeroelastic calculations were performed.

	1st Torsion Freq.	2nd Flap Freq.	3rd Flap Freq.	C.G. equiv.	Control stiffness
EC135	100 %	100 %	100 %	27 % equiv. chord	100 %
Modified Rotor	99.3 %	100.7 %	101.3 %	27.2 % equiv. chord	100 %

Table 1: List of changes in parameters influencing flutter

3.3.2. Drive train

For drive train stability the impact of the new main rotor on the drive train's natural torsion frequencies was investigated. The changes were not significant compared to EC135 series. The new rotor (and the serial EC135 rotor) has lead-lag dampers acting from flexbeam to control cuff. Therefore collective main rotor lead-lag modes, which influence drive train stability, also are damped by the lead-lag dampers. This strongly supports torsional stability of the drive train and engine control system. The 2nd drive train frequency is slightly lower, which increases the margin of this mode to the main excitation frequency of 4/rev. Due to these minor shifts of drive train properties, no explicit calculation of stability margins for the engines in the low frequency range was performed before first flight.

3.4. Vibratory hub loads

The vibratory hub loads (4/rev) were calculated for level flight conditions at different flight speeds for the isolated rotor. The calculations were performed with the internal free wake model of CAMRAD II. Additionally a coupled CAMRAD II - CFD calculation was done using methods described in [3,4]. This was however the first time during a rotor design process at Eurocopter, that vibratory hub load prediction by CAMRAD II and coupled CAMRAD II – CFD calculations could influence the design.

During design phase different rotor blade variants were investigated. The aerodynamic twist characteristic was the main varying parameter. This parameter has nearly no influence for the topics considered before. Here it is assumed to be key to good balance between high performance in hover and acceptable vibratory hub loads in cruise flight condition.

As the design proposals converged, the effort of supporting the design process by CAMRAD II calculations was taken. The vibratory hub load versus flight speed characteristic was calculated for two variants. Version 1 had larger overall twist than version 2. The rotor diameter and planform of the two versions were the same. The dynamic properties were very similar. For comparison a baseline calculation for the EC135 rotor was performed. The EC135 rotor blade has smaller radius and twist than versions 1 and 2. As the calculation results are very sensitive to the aerodynamic modelling in the tip area due to the lifting line theory and to the wake models these parameters were varied to achieve a robust simulation. The results of the calculation cases, given in Table 2, were averaged for the hub load prediction. The results for non-rotating 4/rev pitch and roll moment and vibratory thrust amplitudes are shown in Figure 4 to Figure 6.

Inflow model	Tip vortex location	
Free wake, single peak	98 % Radius	99 % Radius
Free wake, dual peak	98 % Radius	99 % Radius

Table 2: Parameters, varied for averaging of hub load prediction results

Additional coupled calculations with CAMRAD II and CFD were performed for the flight conditions given in Table 3. Drive train, airframe and control chain models, as proposed in [4], were not taken into account due to its high effort.

True Airspeed	130 kts
Rotor advance ratio	0.31
Flight speed Mach number	0.2
Blade tip Mach number	0.661
Rotor shaft pitch angle	-6.3°
Rotor shaft roll angle	-2.2°
Thrust coefficient	0.0071
Rotor hub pitch moment coefficient	1.111×10^{-5}
Rotor hub roll moment coefficient	1.067×10^{-5}

Table 3: Flight conditions for coupled CAMRAD II – CFD calculation

Only the flight condition of Table 3 was investigated. After the calculation it was decided to perform no more calculations with coupled CAMRAD – CFD due to the long duration for one velocity case.

After convergence of the weak coupling calculation mixed results are obtained. Both agreement and differences with the free wake CAMRADII model were seen. Due to its very high effort to generate results and the limited time frame only the free wake calculations were considered at that stage of design instead of the hub load prediction with CAMRAD – CFD coupling.

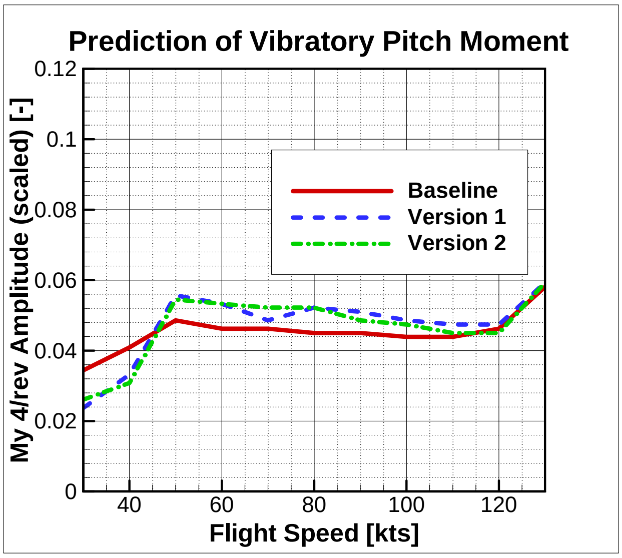

Figure 4: Vibratory pitch moment (scaled) versus flight speed

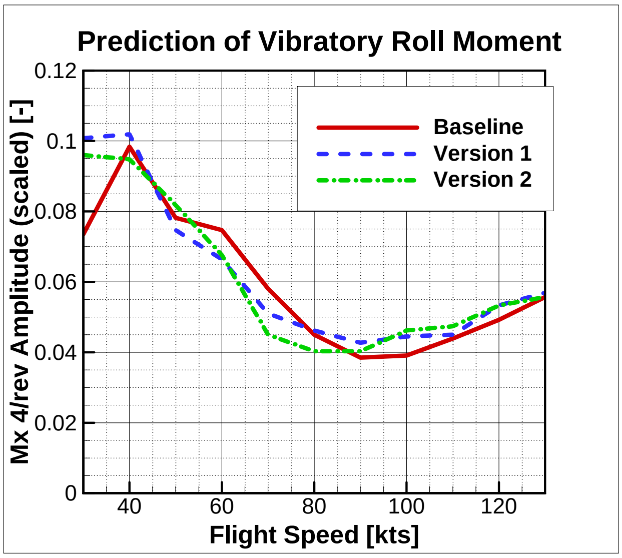

Figure 5: Vibratory roll moment (scaled) versus flight speed

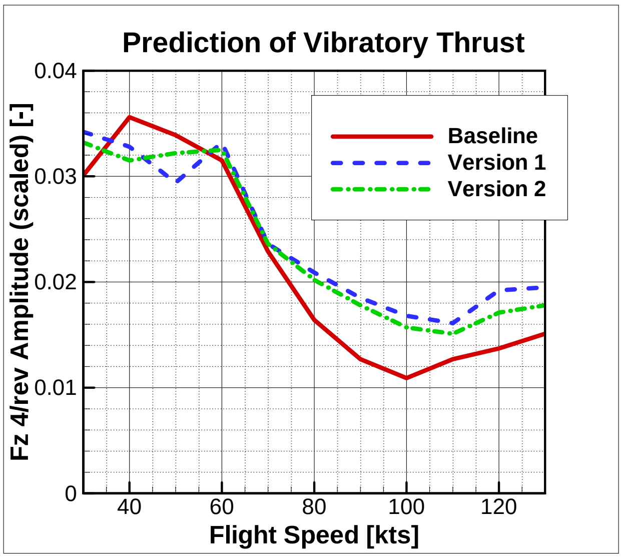

Figure 6: Vibratory thrust (scaled) versus flight speed

A comparison between the baseline amplitudes and the hub load amplitudes of the modified models showed a slight increase in moments and force for the new versions. The version with larger twist in this case shows the larger hub load increase. These results were considered within the design process and influenced the magnitude of main rotor parameter changes, which were realised for flight testing. Especially the level of twist was limited in a way to achieve the aimed performance increase and simultaneously keep the vibratory hub loads in an acceptable range.

After flight tests the free wake hub load calculations were repeated with the latest model and validated against the flight test results. For flight test evaluation the non-rotating vibratory pitch and roll moments and thrust were calculated from main gear box strut forces, measured during flight F0062 of EC135 S/N 0832, which was equipped with the prototype rotor.

The comparison between CAMRAD II hub load calculations and the measurement was done for a flight speed sweep in level flight conditions. The main rotor model was updated according to final design data and whirltower test results. The trim conditions (attitude and moments acting on the rotor shaft) from flight F0062 were used for the level flight trim in the calculations. The free wake parameters, given in Table 4, were varied. The tip vortex location is unknown, but has to be given by the CAMRAD II user. Therefore a lot of attention was given to investigate the influence of this parameter.

Tip vortex location [%R]	91	92	93	94	95	96	97	98
Single peak	x	x	x	x	x	x	x	x
Dual peak	x	x	x			x		x

Table 4: Parameters, varied during model validation

The best overall agreement between simulation and measurement was achieved with the dual peak free wake model and a tip vortex location at 93 % of the main rotor blade radius.

Figure 7 to Figure 9 show the characteristics of vibratory pitch and roll moments and vibratory thrust for flight test and calculations.

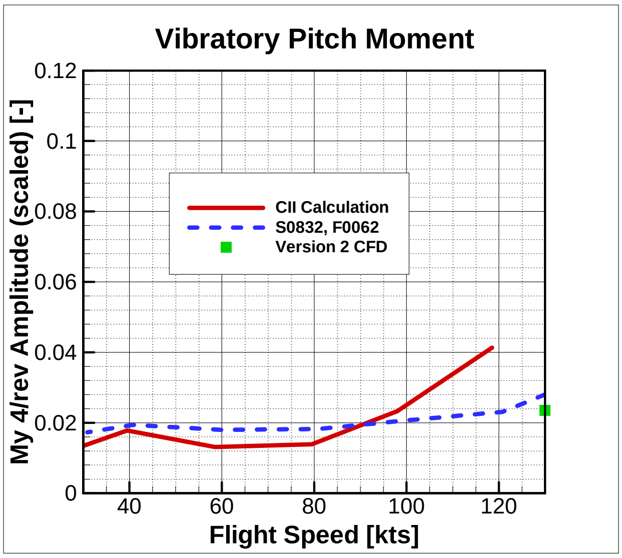

Figure 7: Vibratory pitch moment (scaled) versus flight speed, calculation and measurement

The results from the coupled CAMRAD II – CFD calculation for version 2 is also included in the graphs. Figure 10 shows a wake visualisation for this case. Version 2 was close to the rotor blade, tested in flight.

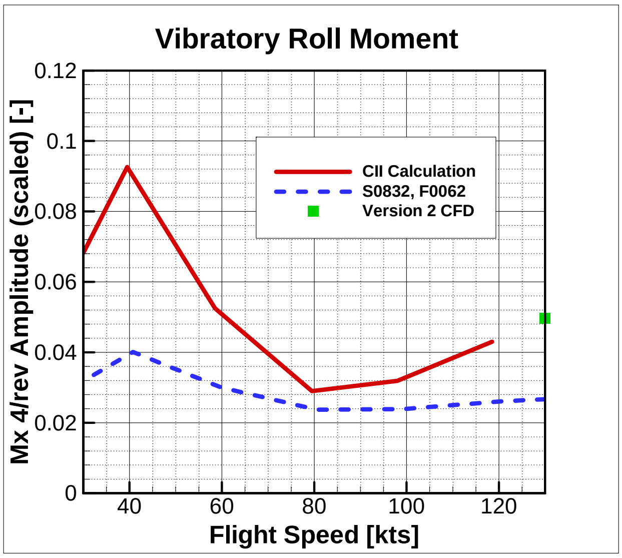

Figure 8: Vibratory roll moment (scaled) versus flight speed, calculation and measurement

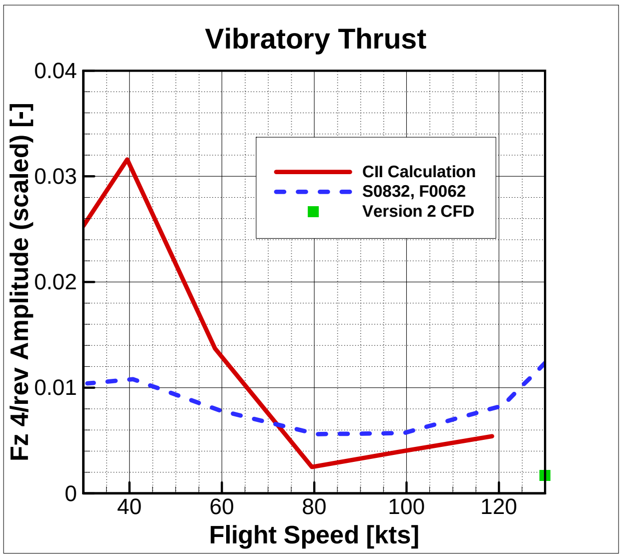

Figure 9: Vibratory thrust (scaled) versus flight speed, calculation and measurement

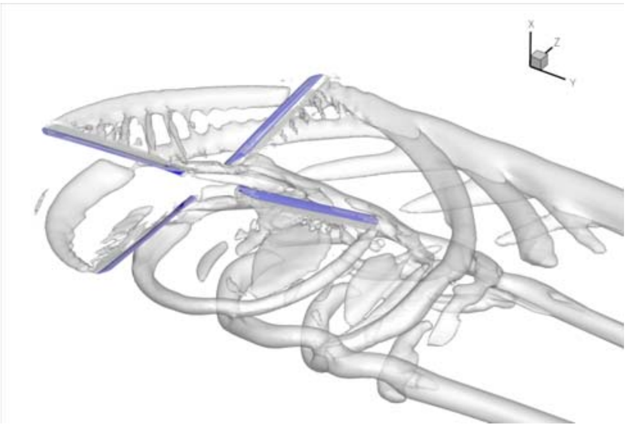

Figure 10: Wake visualisation for version 2

The trends are captured well but the absolute values do not agree satisfactory over the whole flight speed range. It is possible to create good agreement in certain speed ranges by varying the parameters of Table 4, but the absolute vibration prediction over larger flight envelope remains a future challenge for industrial application.

It was possible to influence the rotor blade design in a very early stage by "delta-considerations" between a baseline model and two design variants. Flight testing showed that the "delta-considerations" - achieved by averaging the calculation results (Table 2) - agree quite well with reality.

So far dedicated calculations with CAMRAD II – CFD coupling for model validation were not performed due to its large time effort. It would be desirable to do these calculations for establishing and validating a reliable coupling procedure for future applications. This procedure should also be standardised for easy and fast implementation. From a dynamic and vibrations point of view a reliable and easy to use vibratory hub load prediction would ease and speed up the rotor design process where no similar existing rotor could be used as baseline.

4. ANTI VIBRATION SYSTEMS

As mentioned in the previous chapters, the rotor modification in favour of performance has slight influence on the vibratory loads. In addition to the targeted compromise during the rotor design all present and future anti vibration measures were reviewed. The current series EC135 is equipped with an isolation system (ARIS) [5] and lateral placed passive absorbers in the cabin [6]. With this equipment low cabin vibration within the complete flight envelope is achieved. Especially due to increase of rotor speed the effects on efficiency of the present installed passive vibration reduction systems had to be estimated.

The efficiency of ARIS was simulated for larger RPM bandwidth (96% - 106% nominal RPM). Figure 11 shows the graphical representation of the transmissibility. Here, the high isolation rate at the centre frequency can be observed, but also its reduced vales outside this tuned point. Within the updated RPM range an efficiency decrease by approximately one order of magnitude can be observed. Equivalent behavior is known from the passive cabin absorber as its principle is the same.

The systems principle, shortly repeated, is based on minimisation of the vibration level by creating an opposite directional force field in the cabin that superposes the existing rotor-induced vibration field. Three main components are used in combination with a Filtered x Least Mean Square (FxLMS) algorithm: linear electro-mechanical actuators, feedback accelerometers and an integrated power amplifier and control computer. A schematic overview of the system is given in Figure 12.

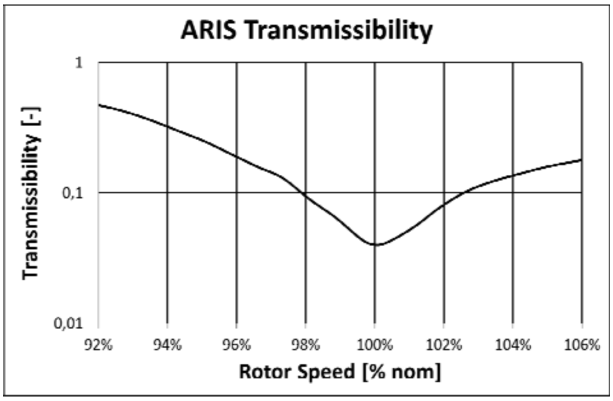

Figure 11: ARIS transmissibility

Up to four actuators and eight sensors can be placed in different directions within the cabin subfloor. The possible application of this multiple axis active anti vibration system for the improved rotor was first explored by simulation. Existing transfer functions of the helicopter airframe in combination with excitation levels were used in the model. The actuator power and control laws were taken from existing flight proven technology. It was shown that the sizing and the capability of vibration minimization of the active anti vibration system promise adequate margin for the EC135 with modified main rotor and even reduce the vibration level.

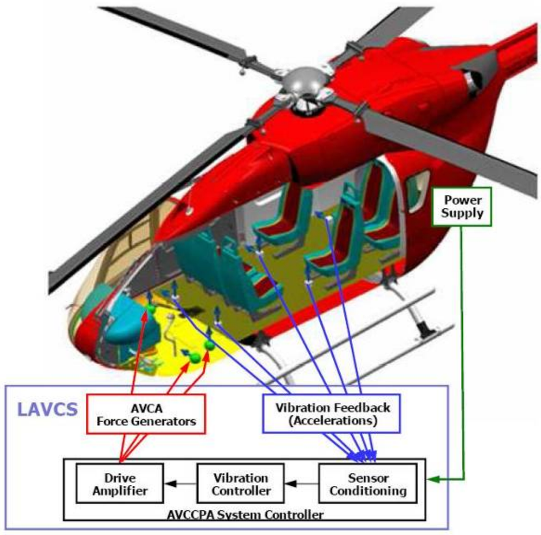

Figure 12: Schematic block diagram of the active vibration control system [5]

5. TESTS

After design freeze, several tests were performed to verify the improved rotor and finally the helicopter itself. For dynamics, three specific tests were used: whirltower, ground test and subsequently flight test.

5.1. Whirltower

Before first flight the new main rotor was tested on a whirltower.

The frequency and damping of the first lead-lag mode and the placement of the first three flap modes were main target of this test from a dynamics point of view. The rotor modes were excited by hydraulic actuators. Their bandwidth limits the maximum frequencies, which can be determined. Due to the large aerodynamic damping the first flap mode could not be identified.

In the fan diagram of Figure 1 the measured data during the whirltower test can already be compared with the calculated frequency characteristics. The measurements are represented by red ‘x’. The agreement for the first lead-lag mode is good. Also the second flapping mode is represented well by the calculations. Coupling effects between the third flapping, first torsion and second lead-lag modes can be observed. Here the calculations do not fit the measurement as good as for the second flapping and first lead-lag modes.

5.2. Ground tests

5.2.1. Fuselage ground test

Since the initial design of the EC135 in 1996 [9] the fuselage was continuously updated. In order to verify the latest modifications and to check the hub load transmissibility in combination with the different anti vibration systems a full scale shake test was performed at DLR test facilities in Göttingen (see Figure 13).

Figure 13: Shake test (© Eurocopter)

A serial EC135 was suspended and excited through different series of up to four 0.2kN - 2 kN shaker configurations (hub and part excitation). Realistic in-flight forces and moments were used. In preparation to check new anti-vibration systems, the fuselage was modified and prepared for maximal four actuators in two directions (lateral and vertical) and eight sensors.

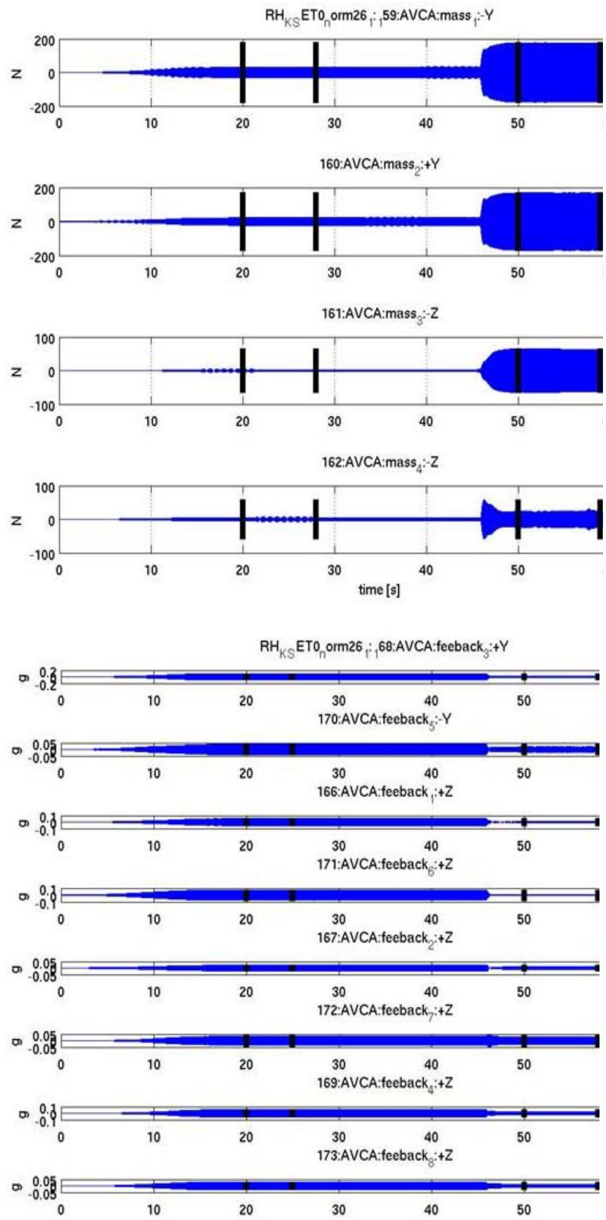

Figure 14: AVCS Vibration level

Several configurations have been checked in which the AVCS was actively controlled against the vibrations induced by the different shakers. Figure 14 shows the vibration and force levels during one of the tests. Here, the actuators were installed in both lateral and vertical direction as well. The upper plot of Figure 14 shows the force output of the respective actuators during one loop of active control. The lower plot shows the vibration levels at the sensor positions. Two sensors were installed in lateral direction and six in vertical direction distributed along the cabin floor. At approximately 46s the system is activated and after a few seconds convergence is reached. At almost all vibration channels a strong reduction of vibration is seen. Simultaneously accelerations on the ARIS components were measured and analysed to confirm the correct operation in combination with the AVCS. As shown in [7] during prototype flight testing with four actuators, large vibration reduction is achievable and even with slightly increased vibratory loads the general vibration in the fuselage could be reduced with respect to current EC135.

5.2.2. Torsional stability

Before the first flight, torsional stability of the drive train was investigated by ground tests. The helicopter was tied down and the pilot excited the drive train by collective control step- and sine inputs. Figure 15 shows as example a step input. Starting point was a collective setting of approximately 30 % of maximum collective.

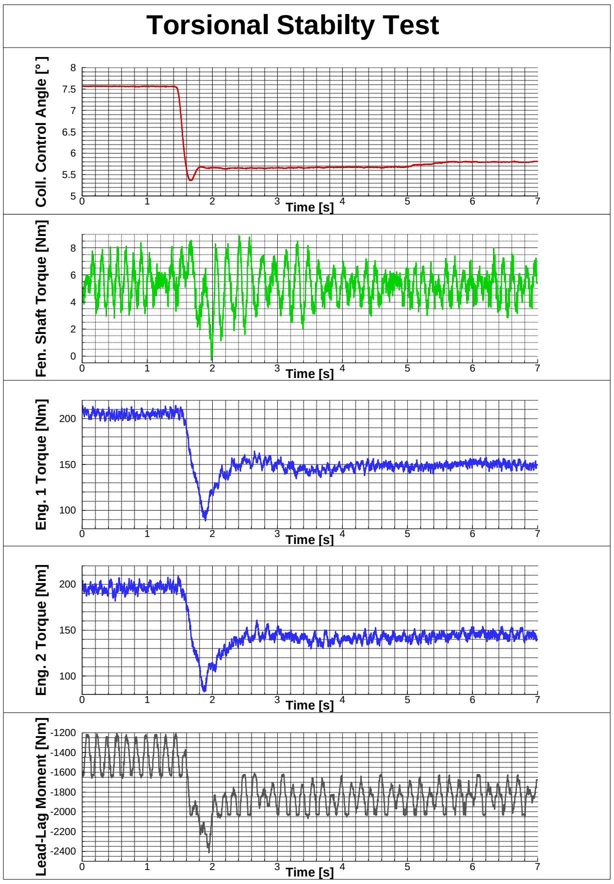

Figure 15: Torsional stability test on ground

In the figure the collective control angle, the Fenestron® drive shaft torque, the torques of engine 1 and engine 2 shafts and the main rotor lead-lag moment can be seen. Nearly no oscillation excitation due to the step input can be seen in the figure. If the characteristics are filtered in the range of the drive train natural frequencies, a slight amplitude increase and subsequent decay can be observed. The drive train and engine control remained stable during the whole tests. Good stability margins also were shown during similar tests in flight.

5.3. Flight tests

After receipt of the flight clearance subsequently to calculations and ground tests a flight test campaign was started. From dynamics and vibrations point of view it mainly consists of ground- and air resonance tests and rotor induced vibration investigation. One blade of the main rotor was instrumented. Additionally, all main gear box struts were instrumented with strain gauges to measure the strut forces in flight.

5.3.1. Ground and air resonance

Ground and air resonance tests were conducted at a very early stage of the flight test program. Before first flight ground resonance stability for the mass and C.G. configuration of the first flight was demonstrated. Afterwards the extreme values of the mass envelope were tested on ground and in flight.

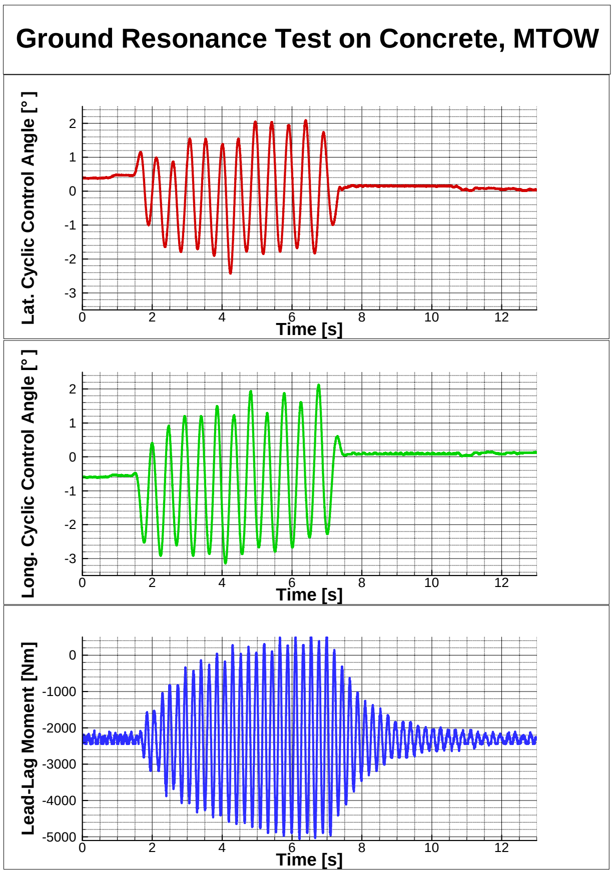

Figure 16: Ground resonance test on concrete

The tests were performed by stick whirl excitation. The ground surface, the helicopter's weight, the main rotor speed and the collective control setting were varied during the tests. As example, Figure 16 shows lateral and longitudinal cyclic control and lead-lag moment. The helicopter mass was approximately 3 tons and the test was carried out on concrete surface. The lead-lag moment characteristic shows sufficient damping after the end of stick whirl excitation.

For air resonance investigations the main rotor was excited by stick whirl in flight. The tests were performed in hover, level flight, climb and descent. Figure 17 shows lateral and longitudinal control input and the resulting lead-lag moment for a descent flight with low helicopter gross mass. As for ground resonance, the lead-lag moment oscillations decay fast after the end of the stick whirl. Only the 1/rev oscillations due to the forward flight speed remain.

The helicopter with the new main rotor showed similar stability margins for both ground and air resonance than the serial EC135 despite its increased rotor size.

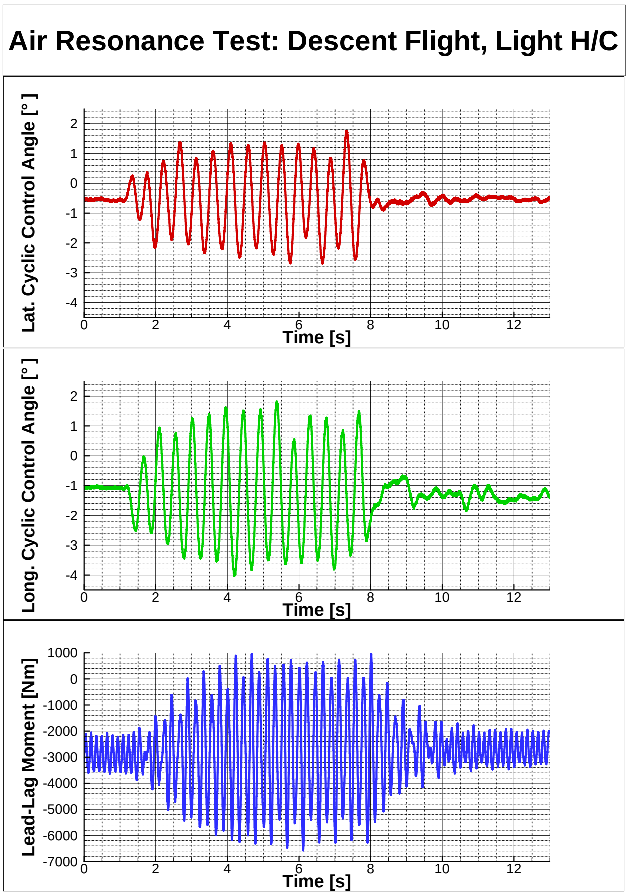

Figure 17: Air resonance test in descent flight condition

5.3.2. Vibration flight test

For evaluation of the rotor induced vibrations, several flight manoeuvres were performed. The rotor blade bending moments and gear box strut forces were measured to determine the loads transferred to the airframe. The gearbox strut forces have been post-processed to represent non-rotating hub moments and forces. Exemplary, the characteristics of vibratory pitch and roll moment and vibratory thrust versus flight speed are depicted in Figure 7 to Figure 9. The measured levels were in the range of the serial EC135.

6. CONCLUSION AND OUTLOOK

A prototype EC135 with modified rotor and engines targets increased performance in hot and high environment. This paper presents necessary steps within the design and test phases to successfully prepare and support flight clearance and flight testing of the EC135 prototype with modified rotor and engines from dynamics point of view.

Different phases in the validation process have been shown and beside the classical investigation of rotor dynamics and stability issues as ground, air resonance and torsional stability special attention was turned to vibratory hub loads prediction.

To investigate the effect of increased twist on vibratory hub loads a vibration prediction by CAMRAD II free wake models and CAMRAD II – CFD coupling was performed in a very early design stage to support the design process. It was possible to influence the process by the free wake calculation results. A good compromise between performance increase and vibratory hub loads could be achieved. Considering the trends to a baseline model the vibration prediction with the free wake models of CAMRAD II gave very good results. The calculation results were validated against flight test measurements and represented the vibratory hub loads versus flight speed trends but the absolute accuracy was not satisfying.

The hub load prediction was supported by CAMRAD II – CFD coupled calculations. However the results seemed not to be fully reliable despite the high effort to perform these calculations. A reliable, standardized and fast process to perform such coupled calculations is highly desirable and would help to ease decisions concerning several rotor blade design parameters.

Nevertheless by using sophisticated calculation methods and early feedback in the design phase a well-balanced result of performance and dynamics of the EC135 is achieved. The performance increase targets could be achieved and simultaneously an acceptable vibratory hub load level was secured by early hub load simulations.

By implementing active anti vibration systems the vibration level of the helicopter could be decreased even below the level of the serial EC135.

7. REFERENCES

[1] Attlfellner, S., "Eurocopter EC135 Qualification for the Market", presented at the 22nd European Rotorcraft Forum, Brighton, UK, September 1996

[2] Johnson, W., "Technology Drivers in the Development of CAMRAD II", AHS Specialist's Conference on Aeromechanics, San Francisco, CA, January 1994

[3] Dietz, M., Dieterich, O., *"Towards increased industrial application of rotor aeroelastic CFD"*, Proceedings of the 35th European Rotorcraft Forum, Hamburg, Germany, September 2009.

[4] Dieterich O., Konstanzer P., Dietz M., "*Vibration Loads Prediction in the Age of CFD*", 36th European Rotorcraft Forum, Paris, France, September 2010

[5] Braun, D., "*Development of Antiresonance Force Isolators for Helicopter Vibration Reduction*", 6th European Rotorcraft and Powered Lift Forum, September 1980.

[6] Rottmayr, H., Popp, W., Mehlhose, R., "*Application of Modern Vibration Control Techniques on EC135 and Future Trends*" 23rd European Rotorcraft Forum, Dresden, Germany September 1997

[7] Hoffmann F., Konstanzer P., Priems M., Chemin J., "*Active Cabin Vibration Reduction for Jet-smooth Helicopter Ride*", 35th European Rotorcraft Forum, Hamburg, Germany, September 2009.

[8] Priems M., Dreher S., Konstanzer P., Hoffmann F., Kerdreux B., Jouve J., *Active Cabin Vibration Control for Light Single and Twin Engine Helicopters,* 68th AHS Annual Forum, Fort Worth, USA, May 2012

[9] Kampa, K.; Enenkl, B.; Polz, G.; Roth, G. "*Aeromechanic Aspects in the Design of the EC135*" 23rd European Rotorcraft Forum, Dresden, Germany September 1997