Model Based H_∞ Control for Helicopter Vibration Reduction

- Flight Tests with Active Trailing Edge Flaps-

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Abstract: Since 2005, Eurocopter is operating an experimental helicopter test bed based on BK117/EC145 and equipped with piezo-actuated trailing edge flaps on the four-bladed hingeless main rotor. Benefits for such active rotor systems are seen in different disciplines as vibration reduction, BVI (blade vortex interaction) noise reduction, performance improvements, load reduction, automatic tracking and stability enhancement. First impressive results concerning the vibration reduction potential of this kind of rotor systems were achieved applying a semi-empirical multiple input-multiple output feedback controller in the time domain [1]. In parallel intensive studies were launched analyzing the applicability of advanced control theory to active rotor control. Eurocopter and the Institute of Flight Mechanics and Flight Control of the Universitaet Stuttgart (IFR) identified the H_∞ control concept as a promising candidate for performing simultaneous control tasks such as vibration reduction in combination with rotor stability improvement. The first demanding step towards this direction consisted in the demonstration of adequate vibration reduction capabilities by a model based approach for control design. Due to the flexibility of helicopter main rotors, an adequate plant model leads automatically to a high order model totalling to more than 50 states for the plant model. Although model reduction is a 'must' due to this reason, the designer has to absolutely rely on theoretical procedures for the determination of controller elements.

This paper presents the design of a completely model based vibration controller of type H_∞ as well as the realization on an active rotor system including successful flight test demonstration.

1. INTRODUCTION

Since decades rotorcraft engineers are fascinated from the potential of active rotor control by fast blade pitch changes allowing to modulate the lift distribution over the rotor disk beyond the first harmonic. The lift distribution over the rotor disk directly affects vibration, noise, performance and fuel consumption as well as stall delay, the later issues especially in highly loaded flight regimes. Therefore, adequate usage of the additional rotor control degrees of freedom – such as individual blade pitch for blade root actuated systems, trailing edge flap deflection for flap actuated systems or blade twist change for rotor systems with active twist – will lead to significant advantages in the disciplines listed above. Nevertheless, the control input typically has to be carefully selected because in the similar manner the rotor behaviour might be improved, it can also be degraded by disadvantageous choice of control. In the past, most activities in the field of rotor active control were dedicated to vibration and BVI noise reduction – topics which are disadvantageously inherent to rotorcrafts thus significantly reducing passenger and public acceptance compared to fixed wing aircraft. The high vibration and noise levels are mainly based on the unsteady aerodynamic environment of the rotor blades encountered during rotor revolution in forward flight.

For the vibration reduction task, Eurocopter developed in the past a semi-empirical multiple input-multiple output feedback controller in the time domain which uses dynamic compensators tuned to blade passage frequency [2]. This type of controller was successfully flight tested on the BO105 with blade root actuation as well as on the follow-on test bed of EC145 size with piezo-actuated trailing edge flaps [1, 3]. The flight tests underlined the potential of the selected control concept with respect to different actuation concepts for active rotor control and also with respect to different helicopter types. Nevertheless, the controller design asks for open loop flight tests in a first step for setting up the feedback loop including the gain matrix which incorporates 18 matrix elements for simultaneous feedback of vertical thrust, hub pitch and hub roll moment at blade passage frequency. It is obvious that for gain matrices of this size, trial and error procedures – even in a systematic way – will not lead to success. Controller design concepts which – compared to conventional HHC (higher harmonic control) approaches – are based on advanced control theory such as LQY type concepts were intensively studied during the development phase of the semi-empirical controller e.g. for controller layout. Therefore, the next logical step in the vibration controller development consisted in the application of advanced control theory not only for controller layout but also for the entire model based control design process which – if successfully mastered – allows the application of controllers of arbitrary complexity. Among the different controller concepts suitable for vibration reduction, the H_∞ control concept was selected as representative concept which offers the potential to favourably modify the dynamic behaviour of the rotor system also at other frequency ranges thus allowing to introduce additional simultaneous control tasks.

2. ACTIVE ROTOR CONTROL

2.1 Active Rotor Control History at Eurocopter

The Eurocopter group has a long tradition in active rotor control. The active rotor control activities started with a modified three-bladed SA 349 Gazelle helicopter [4, 5] flight tested by former Aerospatiale in France in closed loop throughout the whole flight envelope in 1985. The experimental system featured on the one hand multicyclic actuators series-mounted with the conventional primary flight control actuators for the 3/rev activation of the non-rotating part of the swashplate and on the other hand a self-adaptive control system for computing the optimum control law for vibration reduction. For vibration reduction, representative higher harmonic blade pitch input was reported to approximately 0.8 deg amplitude at 2/rev, very low amplitudes for 3/rev and approximately 0.3 deg at 4/rev in the rotating system.

About ten years later, former MBB on the German side modified a serial production four bladed BO105 for active rotor control by replacing the pitch links in the rotating system by hydraulic actuators provided by ZF Luftfahrttechnik (ZFL). This concept is also known under the designation IBC for individual blade control as each blade is related to its own specific actuation device. Several actuator designs were tested for a BO105 main rotor in flight and full scale in the NASA Ames wind tunnel [6]. The amplitudes of the actuators used for the last successful closed loop flight tests amounted to approximately 1.1 deg [3]. As next step, Eurocopter realized a more advanced active rotor control solution based on piezo actuated trailing edge flaps [1]. A BK117 airframe serves as test bed while the main rotor was significantly modified starting from the BK117C-2/EC145 blades in order to integrate the active devices, see figure 1. This test bed was also used for the flight tests of the H_∞ controller and therefore, more details of this experimental system are given in the next chapter.

Figure 1. Experimental system featuring active rotor with trailing edge flaps

2.2 Experimental System

For the integration and successful performance of the active trailing edge flaps on the BK117 test bed, Eurocopter applied several modifications to this helicopter. Major topics are rotor blades including flaps, power and signal transfer and – of course – the control system itself. Due to the nature of the actuation system the main rotor blades required major changes. The dynamic layout of the rotor system was not only altered by structural modifications regarding the installation of the flaps but was also tuned towards higher efficiency of the active flaps by lowering the torsion stiffness [7]. Each blade is designed to incorporate flap units of 300 mm spanwise extension. The piezo driven flap units were provided by former EADS CRC, now EADS IW [8].

Regarding the experimental test bed electric power is provided from the airframe by a brushless transducer installed below the gear box. Complementary sensor and control data are transmitted between the non-rotating and the rotating system by an optical bi-directional data link [9]. The cylindrical compartment mounted on the rotor hub houses signal conditioning and processing as well as power distribution. The next generation of the power distribution and acquisition unit on top of the rotor hub being already in the laboratory test phase will fit under conventional hub caps avoiding the aerodynamic disadvantages of the current prototype design. For active rotor control, the test bed is equipped with the control computer for operating the active flaps in open and closed loop mode and with a data acquisition system processing and conditioning the sensor signals for feedback issues. The control computer is based on PowerPC technology and is part of a commercial rapid prototyping solution for control. This hardware solution was already successfully tested in the closed loop campaigns of the BO105 with IBC presented above. The flight test engineer has access to the controller by a touch screen whose set-up is also integrated part of the rapid prototyping control solution.

2.3 Control System Evaluation

2.3.1 Transfer Matrix Control Approach

First theoretical activities are based on the representation of the helicopter plant by a constant matrix *T*. This matrix relates the Fourier coefficients of specific harmonics of the input e.g. the control vector for flap actuation or similar to the harmonics of the output e.g. the vibrations in the airframe or the hub vibratory loads. Thus, the sine and cosine coefficients of the vibrations can be represented by

$$y = T\,u + y_0, \tag{1}$$

where y contains the Fourier coefficients of the vibration vector, u the Fourier coefficients of the input and y_0 the Fourier coefficients of the vibrations without active control input. Using Fourier coefficients this formula underlines the frequency domain character of this control approach. Control objective is to select the control vector u in such a way that y is set to zero or adequately minimized. This approach is suitable for vibration controllers with low bandwidth assuming that helicopter plant dynamics is faster in equilibrium than the controller reacts. A detailed and schematic overview for the different applications of the transfer matrix approach is given in [10]; successful closed loop flight tests with related control concepts are reported in [4, 11].

2.3.2 Disturbance Rejection Control

Internal Model Control

In [12], the authors demonstrated that the transfer matrix control concept presented above can be understood as classical narrow band disturbance rejection. Therefore, it was a logical step to move to conventional control theory in the time domain thus avoiding the disadvantages of frequency domain controllers and to close the gap to modern control theory. The helicopter plant dynamics can be generally written in state space form as a linear time periodic system as follows:

$$\begin{aligned} \dot{x}(t) &= A(t)\,x(t) + B(t)\,u(t) \\ y(t) &= C(t)\,x(t) + D(t)\,u(t) \end{aligned}, \tag{2}$$

with x as state vector of the plant and A, B, C, D time periodic system matrices. For control issues, state vector variables x or output vector elements y can be used for feedback. Although in theory less powerful than state feedback, output feedback offers advantages regarding the implementation in real world problems by direct usage of the measured signals thus avoiding the needs for observer capabilities. According to the internal model principle presented in [13], dynamic compensators need to be included in the feedback loop which are accommodated to the disturbance signals to be eliminated. The application to the vibration reduction problem by active rotor control is discussed in detail in [2] which also presents an approach to derive the controller gain elements in a semi-empirical manner based on flight test results. The related time domain vibration controller was successfully flight tested as reported in [3] for the experimental BO105 and in [1] for the ADASYS test bed with active flaps.

Model Based H_∞ Control
The IFR is working for several years on model based control concepts for helicopter vibration control and lead-lag damping enhancement. Investigations on time constant and time periodic H_2 and H_∞ approaches were carried out to find an adequate controller for the desired mixture of controller performance and robustness. This paper presents the first experimental flight test data to verify the analytical investigations and underline the practicability of complex high order controllers in today's experimental IBC systems. Therefore, more information on H_∞ is given in the next chapter.

Fully Integrated Multi-objective Control
Beside an overview of different potential tasks for active rotor control such as BVI noise reduction, performance improvements, expansion of the flight envelope and stability augmentation, the authors of [14] discussed the simultaneous performance of vibration and BVI noise reduction as a first integration step towards a multi-purpose active rotor control system. The underlying approach consisted in the transformation of control input degrees of freedom into multi-blade coordinates and a separation into differential (i.e. 2/rev) control inputs for BVI noise reduction and collective and cyclic control input degrees of freedom for vibration reduction.

Nevertheless, in order to add additional tasks such as stability augmentation or load reduction, other approaches has to be considered. For this objective, the controls have not only to be separated by multi-blade coordinates but also by bandwidth separation in order to allow the parallel fulfilment of several active rotor control tasks at the same time. In [15] an approach is presented for simultaneous control of vibration and stability by a decentralized control method.

Among other advanced control concepts, H_∞ control is a potential candidate for building the framework for multi-objective control as frequency shaping of the weights allows a separation of the different controller activities during an integrated design procedure. Intensive studies regarding multi-objective control are still under way by Eurocopter and IFR.

3. MODEL BASED H_∞ CONTROL

3.1 General H_∞ Control Problem

The H_∞ closed-loop shaping approach is based on setting up a standard scheme which incorporates frequency domain requirements to obtain performance and robust stability trade-offs. The control problem is transformed into the standard problem and can be solved under some assumptions [16], which guarantee the existence of a stabilizing controller to achieve the performance required over all frequencies. For a better explanation a classical feedback control system - shown in figure 2 in standard notation - will be considered.

The design objectives can be translated into frequency domain requirements for different transfer functions between the inputs and the outputs of the feedback control system characterizing various performance criteria. For the disturbance rejection on the output, for instance, the transfer function from the disturbance d to output y, known as output sensitivity S_y, is of interest. Ensuring, that the largest singular value σ of the frequency response of S_y is lower than an upper bound ε in the frequency range where the disturbance is active, guarantees the disturbance rejection properties. The H_∞ closed-loop shaping allows to shape the different transfer functions by means of weighting functions *W* that translate a desired frequency response, i.e. a desired closed loop behavior. We say the feedback control system is augmented by the weighting functions. This augmented system can be arranged, as illustrated in figure 3, in a standard form also called the standard scheme or standard problem.

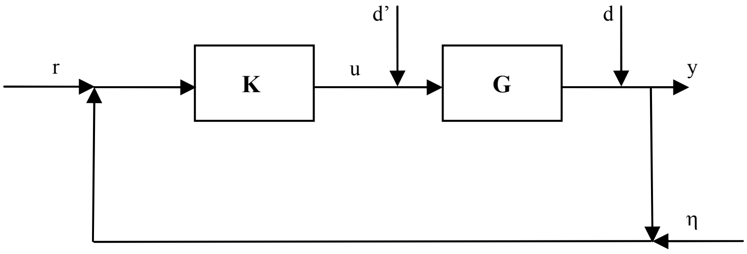

Figure 2. Classical feedback control system

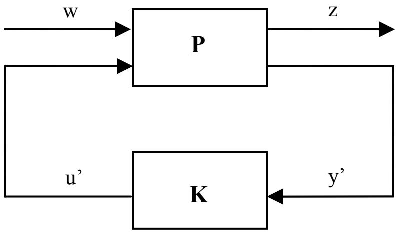

Figure 3. H_∞ standard control scheme

In this figure *w*, *u'*, *z*, and *y'* constitute vector valued signals. *w* is the exogenous input, typically consisting of disturbances and sensor noises, *u*' is the control signal, *z* is the output to be controlled or the error vector to be minimized, and *y'* is the measured output fed back to the controller. The transfer functions *P* and *K* represent the generalized plant and the controller, respectively. The generalized plant consists of the nominal plant *G* and the weighting functions *W*. Solving the standard problem means to find a real-rational proper *K* to minimize the H_∞-norm of the closed loop transfer function from *w* to *z* under the condition that *K* stabilizes *P* [17]. This is equivalent to minimizing the H_∞-norm of the lower linear fractional transformation, which is given by

$$\left\| \Im_l(P,K) \right\|_\infty = \left\| \frac{z}{w} \right\|_\infty = \max_\omega \bar{\sigma}(\Im(P,K)(j\omega)). \tag{3}$$

The quotient *z*/*w* does not denote a division but rather a transfer matrix from *w* to *z*. The minimum of $\Im_l$ is approached iteratively so that the H_∞-norm is lower than an upper bound. The obtained controller *K* would generate an appropriate control signal *u'*, which counteracts the influence of *w* on *z*.

An H_∞ controller can be set up in an observer form, which will be used in the hub vibration rejection case to adapt the controller to varying helicopter main rotor speeds and change the controller vibration reduction performance through a change of the closed-loop shaping filter damping. In contrary to the H_2 controller the state feedback gain and the output injection or observer gain of an H_∞ controller are one way coupled which complicates the calculation and the validation of the controller gains.

3.2 Former Aerospace Applications

The application of H_∞ control for primary flight control is described in [18] for a fly by wire helicopter and in [19] for the VTOL fighter aircraft Harrier. In addition to the experimental applications, H_∞ control is used for the control of the ARIANE V launcher [20] and the IRIS-T air-to-air missile [21] in series production. The control concept is mainly used for primary flight control with a low order linear plant model. In contrary the H_∞ controller for helicopter vibration reduction will be of high order as will be shown in the following sections.

4. APPLICATION OF H_∞ CONTROL FOR VIBRATION REDUCTION

4.1 Plant Model

The linear time invariant state space models used for the calculation and verification of the H_∞ controller are derived from a comprehensive rotor code [22]. For vibration reduction control the transfer behaviour from the trailing edge flaps to the forces and moments at the rotor hub is necessary. Each of the torsional soft rotor blades incorporates three flap modules at different radius stations. For flight testing, the inner two flaps are mechanically connected and the third flap is replaced by a dummy so the input of the rotor model is reduced to four flap deflections in multi-blade coordinates. The output vector consists of the three forces and the three moments acting on the rotor hub. For modelling the rotor dynamics four flap modes, two lead-lag modes and one torsional mode are considered resulting in a total of 56 states.

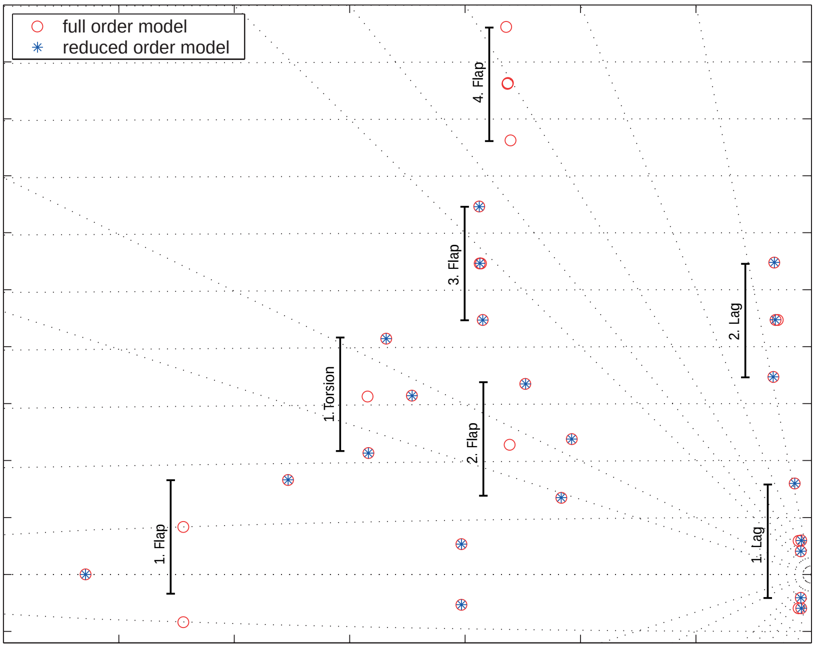

Figure 4. Poles of the full order and the reduced order rotor model

Figure 4 shows a pole plot of the full order linear time invariant rotor model. The model is linearized at a flight speed of 100 kts assuming level flight conditions. Because the order of the plant model directly influences the order of the H_∞ controller, the order of the rotor model has been reduced. The poles which correspond to the differential mode do not influence the input-output behaviour of the linear state-space model and are therefore neglected. The fourth flap mode is of high frequency and is not necessary for modelling the dynamic behaviour at the frequency of the vibrations. Therefore the fourth flap mode is also erased. This results in a reduced rotor model order of 36. The reduced rotor model is used for the controller computation.

The input-output model behaviour of the plant model indicates that there are three rotor modes that can be mainly used for control purpose namely one collective and two cyclic control inputs. So three vibratory hub loads can be eliminated by a linear controller design. The experience shows that the force F_z and the moments M_x and M_y acting out of plane of the rotor blade have great influence on the accelerations at the pilots and co-pilots seats for hingeless rotor designs. Therefore the controller is set up to cancel these quantities.

4.2 Weighting for Disturbance Rejection

The nominal rotor model is weighted in terms of frequency dependent and constant weighting functions. The objectives for the choice of the weighting functions are the desired disturbance rejection at the plant output, the limited actuator authority at the plant input and the robustness against model uncertainty at the plant input and output. Table 1 shows a summary of the different weighting functions and their purpose in the controller design. The generalized plant P of figure 5 is set up analytically resulting in the H_∞ controller design shown in figure 5. The order of the generalized P is 62.

Table 1. Weighting functions of the generalized plant P

Name	**Weighting function**	**Purpose**
S_{yout}	Notch	Vibration reduction
S_{youtc}	Constant	Disturbance rejection
d_{Hout}	Constant	Input uncertainty
d_{Hin}	Constant	Output uncertainty
S_{yin}	Notch	Vibration modelling
KS_y	Low pass	Filtering of bias and control authority
d_{KSyc}	Constant	Control authority

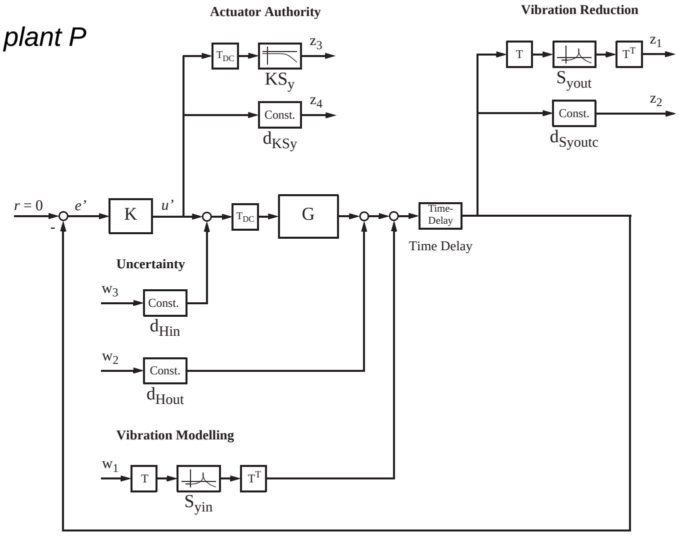

Figure 5. Generalized plant G

4.3 Simulations

Figure 6 shows the excellent performance of the H_∞ controller; the hub load vibrations in the selected hub force F_z and moments M_x and M_y are nearly cancelled out, steady state is reached after three rotor revolutions. The amplitude of the vibrations in the uncontrolled forces is lowered whereas the torque M_z is nearly unchanged. The evaluation of the controller outputs shows that the commanded amplitude of the trailing edge flaps stays within 7 degrees what means that the actuator limits are not crossed. Simulations in the presence of measurement noise show that the controller performance is not affected by the high frequent noise. Robustness studies are carried out demonstrating a good performance of the nominal controller under changing trim conditions. All simulations shows a stable operation, neither a change of the flight speed, altitude, main rotor speed or maneuvers nor simulated failures as the loss of the control signal measurements results in infinite feedback signals. The controller design has not to be changed in the presence of time delays up to six milliseconds, a change of phase in the measured feedback signals of more than 70 degrees still results in a stable controller operation.

5. FLIGHT TEST RESULTS

5.1 Realisation

For implementation purposes, the observer-based H_∞ controller, which is designed in the continuous-time, has been transformed into the discrete *z*-domain giving the same response at the sampling instants as the continuous-time controller does. For this reason, the controller has been further decomposed into sub-modules as shown in figure 7. Performance and robustness investigations with the discrete equivalent controller have been conducted to assess its behavior in closed-loop.

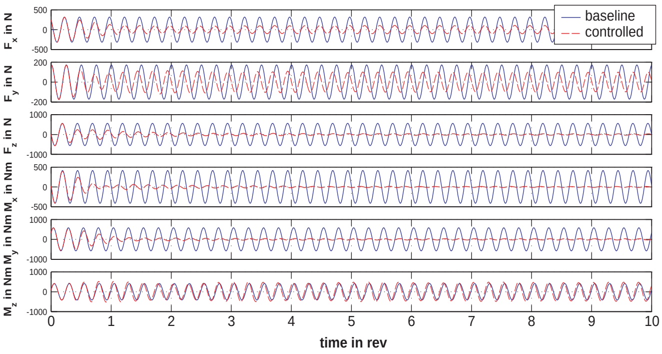

Figure 6. Closed-loop simulation with nominal plant mode

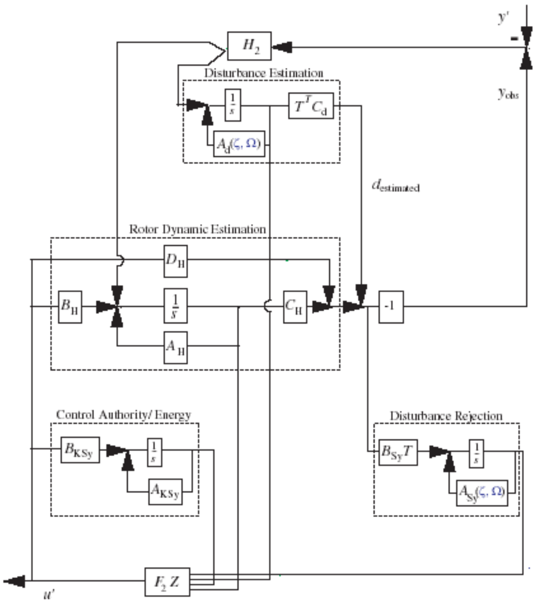

Figure 7. Decomposition of the controller

Moreover, pre-flight investigations were performed before taking the discrete H_∞ controller into flight. These investigations have comprised the evaluation of the rotor model used to design the controller, stability analysis, offline open-loop validation of the observer gain and thus of the estimated disturbance and rotor states, and subsequently ground tests for checking the system in real-time. Some phase deficits between the model and real plant responses (out-of-plane hub loads) have been explored mainly due to up to now non-considered time delays in the control chain. Different models for capturing the error dynamics have been derived with the objective to find out if the controller would be robust against existing discrepancies between model and real helicopter or if an adjustment of the analytical model and subsequently of the controller weighting functions would be necessary. The analytical model has been updated accordingly and the resulting optimized model is used then to re-design the H_∞ controller. The gains of the weighting functions were adjusted to still fulfill the control objectives.

5.2 Flight Test Program

Different control strategies were developed for testing the H_∞ controller taking necessary precautions to avoid system instabilities. In total three different controllers have been established with respect to these first tests. They differ in their level of robustness and whether the collective and cyclic loops could be considered as separated or not. So the following controllers were on hand:

- A decoupled H_∞ controller with high robustness level and low vibration reduction performance,
- a decoupled H_∞ controller with low robustness level and high vibration reduction performance and
- a coupled H_∞ controller with low robustness level and high vibration reduction performance.

The terms “decoupled” and “coupled” are used to designated whether the collective and cyclic loops were considered separately during the control computation or not. Again, the decoupling of the both loops allows the verification of the internal loops of the controller first. The controllers with high level of robustness were designed to keep the response of the controlled hub loads slow. These controllers are stiff and slowly respond to the disturbance. In contrast, the response in the hub loads is faster with controllers with low level of robustness. The controller characteristics and the manually adjustable damping values afforded a safe flight test procedure going through the different control strategies. Starting with a high robustness level, the collective and the cyclic control loops are investigated separately. After testing both loops successively, the same procedure is repeated with a low level of robustness and a high level of performance. The last point of the flight test matrix is a fully coupled controller. This means that the feedback gain is a full-block matrix.

5.3 Experimental Results

To verify the stability and reliability of the controller two flight tests were conducted in 2006: Level flight from 40 kts up to 100 kts (F170) and level flight at 100kts with a variation of RPM from 98% up to 101% (F171). The investigations started with the setup of the different controller settings mentioned in chapter 5.2. The first flight tests were aimed on testing the complete collective and cyclic disturbance feedback with the decoupled and coupled H_∞ controller in level flight from 40 kts up to 100 kts. A pronounced reduction of the 4/rev hub load is achieved by the H_∞ controller. The controlled vibratory hub loads at 40 kts flight speed are showing a reduction of about 90% for M_x and F_z and about 75% for M_y. These very encouraging results are plotted in figure 8. The measured 4/rev gearbox vibrations are presented in figure 9. The gearbox vibrations are below 0.2 g in x- and y-Direction and well below 0.1 g in z-direction and the vibration rating given by the flight test crew was excellent. A second flight test demonstrated the performance of the control algorithm for rotational speed variations (98% up to 101%) in level flight at 100 kts. In figure 10 the hub loads are presented for the second flight. This figure shows that there is no influence of the RPM variation on the controlled hub loads showing the robustness of the selected approach.

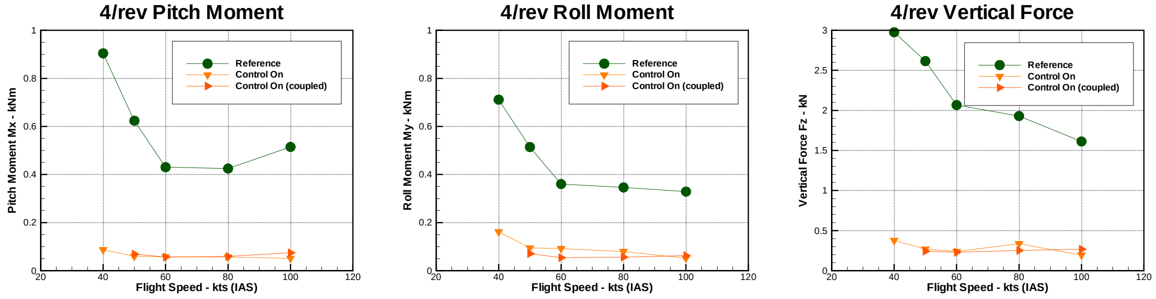

Figure 8. Hub loads vs. level flight (F170)

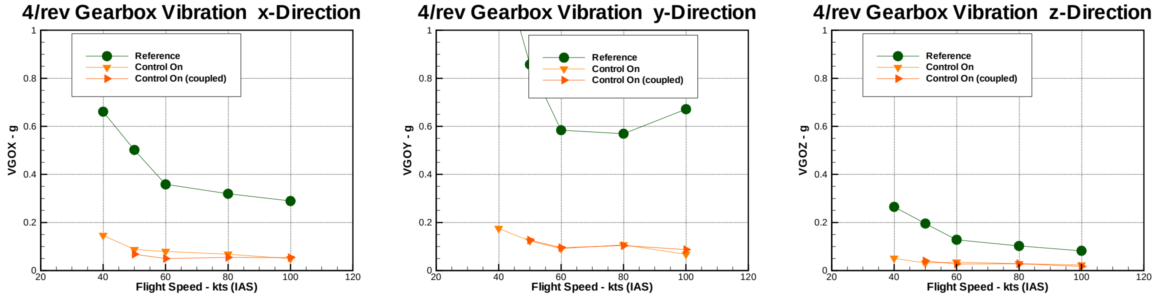

Figure 9. Gearbox vibration vs. level flight (F170)

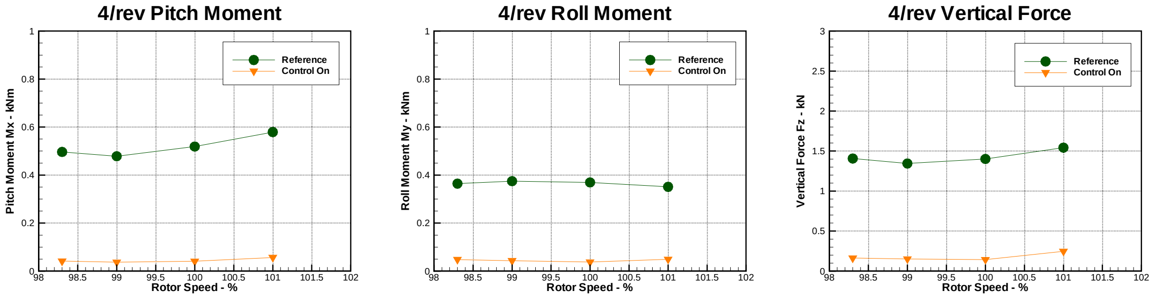

Figure 10. Hub loads vs. rotor speed at 100 kts (F171)

6. CONCLUSIONS

Reviewing the evolution of rotor active control at Eurocopter, complementary trends towards advanced solutions can be observed for actuation devices and control algorithms. The actuation devices moved from the primary rotor control path in the non-rotating system via the rotating system to the main rotor blades thus no longer affecting the primary control chain. Beside improvements regarding safety issues, the inertia of the structure to be actuated was significantly reduced by each development step being beneficial for actuation power as well as for the hereby generated loads.

Looking onto the control system, the rapid evolution of computer technologies affected active rotor control as well in a beneficial sense. The increased hardware capabilities allowed the transition from frequency domain control algorithms to time domain applications. Furthermore, the improved performance of todays' real time systems enables the user to perform complex algorithms in time offering the opportunity to apply modern control theory. Motivated by the progress in these fields, Eurocopter in co-operation with the IFR selected H_∞ control as a representative state-of-the-art concept in order to demonstrate the applicability of modern model based control design. The following conclusions are hereby drawn:

- Flight tests applying active rotor control by piezo-actuated trailing edge flaps showed excellent results with respect to vibration reduction.
- Model based design of active rotor control laws was successfully demonstrated for vibration reduction. To the authors' knowledge, this is a "first" in the world.
- The successful controller design proofs that the underlying models are well representing the real world system behaviour.
- Furthermore, the results showed that complex controllers with a high number of states can be realised and operated in real time with today's technology.
- In further steps, the gained experience to apply model based control allows to implement and to realise additional functionality of active rotor control such as stability augmentation, loads alleviation etc.

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