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Active Rotor Control by Flaps for Vibration Reduction
- Full scale demonstrator and first flight test results -

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Active Rotor Control by Flaps for Vibration Reduction
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An experimental BK117 was the first worldwide flying helicopter with an active rotor system based on piezoelectric driven trailing edge flaps. The related research project called ADASYS aims on the reduction of vibrations as well as blade in flight tracking, load reduction, performance improvement and stall delay. It is a joint task between Eurocopter, EADS CRC, DaimlerChrysler Research Labs and DLR in Germany and is supported by the German Ministry of Economics [1].

The experimental test bed shows several features for active rotor control purposes. The blade design is based on the hingeless rotor of the EC145 with modular units containing the actuation system and the flaps. The data exchange between airframe and rotor uses an optical device and the electric power is transferred via brushless technology. The controller is driven by a rapid prototyping system using computer based tools. A lot of data pickups at the rotor blades, active flap units and in the airframe are used to monitor the whole system.

The flight test campaign started in the year 2005 with investigations on the characteristics of this advanced rotor system. The extensive ground tests were followed by in-flight evaluations like track and balance tests and checks on the dynamic behavior of the system. After confirming a save operation of the test helicopter in passive mode the flaps have been actuated steadily as well as with frequencies up to 5/rev. A remarkable performance of this system was demonstrated with respect to vibrations in open and closed loop mode. These test results built the basis for the design parameters of advanced vibration controllers.

Nomenclature

F_x	Longitudinal hub force
F_y	Lateral hub force
F_z	Vertical hub force
G	System transfer function
M_x	Hub roll moment
M_y	Hub pitch moment
M_z	Hub yaw moment
d_{Hub}	Disturbance (hub)
u_{IBC}	Controller output (IBC actuation)
y_{Hub}	System output (error signal)
Ω	Rotor speed
θ	IBC actuation amplitude
φ	IBC phase

Acronyms

ADASYS	Adaptive Dynamic Systems
BVI	Blade vortex interaction
HHC	Higher Harmonic Control
IBC	Individual Blade Control

1 Introduction

Helicopter designers are fascinated from the technical possibilities offered by a high frequency and independent blade pitch control device for main rotor blades. The outstanding advantages are seen in the higher harmonic control of the lift distribution over the rotor plane directly influencing vibratory rotor loads, blade vortex interactions, stall delay and rotor performance. The Eurocopter group has long term experience in the investigation and development of such higher harmonic and individual blade control (IBC) technologies. During the last years, flight tests in closed loop configuration for noise and vibration control were successfully conducted with a BO105 helicopter, which was equipped with electro-hydraulic actuators. This blade root actuation system, showed a good performance of noise and vibration reduction. Therefore, the active trailing edge flap concept has gained much interest for so-called 2nd generation IBC systems. After extensive theoretical investigations [2] the BK117 S7045 experimental helicopter was equipped with an active blade system based on piezoelectrically driven trailing edge flaps followed by a thorough ground testing. The first flight of this new test bed took place in the year 2005. Flight tests in open and closed loop configuration for noise and vibration control could be performed successfully. This paper describes the actuation system as well as the control algorithm for vibration control. Finally the very encouraging flight test results in closed loop configuration are presented.

2 The first IBC Demonstrator BO105

The first IBC demonstrator operated by ECD was the BO105 S1 helicopter using electro-hydraulic blade pitch actuators provided by ZF Luftfahrttechnik (ZFL) which replaced the pitch links in the rotating frame, see Fig. 1. For safety reasons the blade pitch authority of the actuators was limited by hardware stops to 1.1 deg. Although the authority was further reduced by software limits, the available IBC blade pitch amplitude proved to be sufficient for impressive BVI noise reduction in descent flight [3] and for significant vibration reduction in level flight [4].

Fig. 1: BO105 S1 IBC demonstrator in flight

The control concept of the applied vibration controller was based on the reduction of the disturbing hub forces and moments (see Fig. 2). Tests demonstrated the good performance of the applied vibration controller in level flight conditions as well as in manoeuvre flights. An example of the achieved vibratory hub load reduction in level flight is presented in Fig. 3.

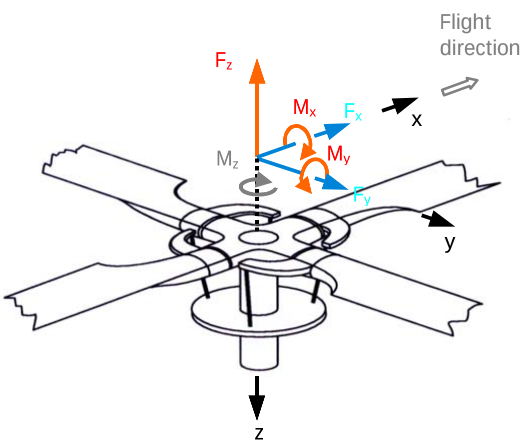

Fig. 2: Hub loads for feedback control

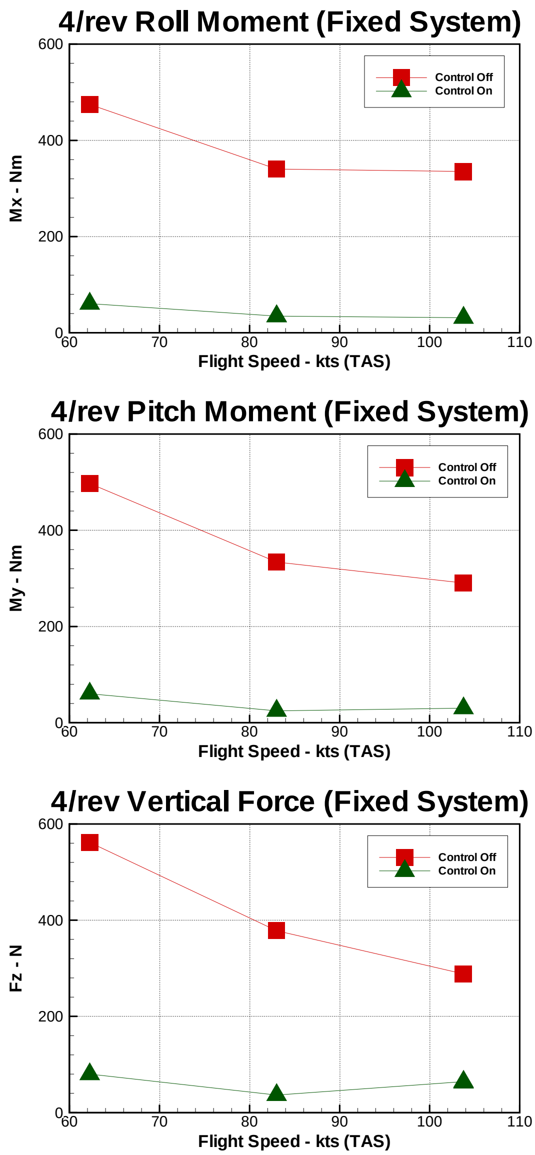

Fig. 3: Controlled hub loads vs. flight speed at nominal rotor speed, BO105 S1

Table 1: Comparison of IBC test beds operated by ECD

BO105 S1	BK117 S7045
Rotor radius 4.9 m	Rotor radius 5.5 m
Nominal TOW 2300 kg	Nominal TOW 3000 kg
Four bladed hingeless rotor (type Boelkow)	Four bladed hingeless rotor (type Boelkow)
Rectangular blade geometrie (NACA 23012)	Advanced blade geometrie [5] (OA series)
IBC by blade root actuation	IBC by trailing edge servo flaps

3 The new IBC Demonstrator BK117

Although the electro-hydraulic system of the BO105 behaved well during the experimental campaign, a promising actuation concept for future applications was seen in piezo-actuated trailing edge flaps. For the new experimental rotor system a BK117 was selected as test bed. Concerning the main rotor system, it should be noted that the rotor hub of type Boelkow is the same for both helicopters. Table 1 gives a comparison of the test helicopters.

3.1 IBC by Trailing Edge Flaps

Flap Location and Dimensions

An important design parameter is the radial position of the flap. Parametric studies revealed that for BVI noise reduction purposes the flap should be shifted as close as possible to the blade tip. Due to the blade tip design with a swept back planform, the outboard end of the flap was limited to radius station 4.9 m (0.89R). In the contrary the most beneficial location for vibration control is in the mid range span at 4 m (0.73R). Flap chord and the torsional stiffness of the blade impact the blade response as well. Lower torsional blade stiffness and smaller flap chords support the servo effect of the flap and helps to limit the needed actuator power [1].

Actuators

The flap actuator has to withstand high mechanical loads and should feature low volume and slim shape to fit into the blade section. A piezoceramic system was chosen due to its good controllability and efficiency as well as its remaining inherent stiffness in case of a power loss.

Rotor Blades

Basis for the implementation of the flaps was the EC145 main rotor. The planform of the blades has an inboard tapering and features a swept back parabolic tip. The design of the blade was modified to integrate the active trailing edge flaps with characteristics as shown in Table 2. The flap system consists of three identical units with an individual length of 0.3 m. Dedicated studies revealed that one pair of the available piezoelectric actuator is able to run a flap of 300 mm extension and a chord of 50 mm. The trailing edge of the blade was cut out and the foam used as support between the upper and lower blade skin was substituted by a flat box made from carbon fiber. The box is open at the aft side. After inserting the units into the blade (see Fig. 4) all the parts are screwed and sealed to ensure the stiffness and strength requirements of the blade, as well as the protection of the flap actuation system against humidity.

Table 2**:** Flap geometry

Chord	0.05 m, 15 %
Max. length	0.90 m, 0.16R
Radius station	3.8 - 4.9m
Unit 1	3.95 m, 0.718R
Unit 2	4.25 m, 0.773R
Unit 3	4.55 m, 0.827R
Max. flap angle	± 10 deg

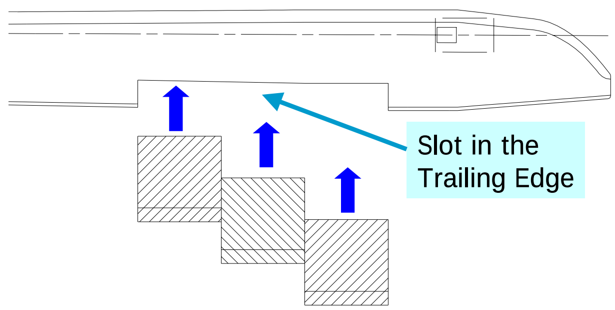

Fig. 4: Installation of the flap units from the trailing edge side

The actuator/flap unit is self-contained and can be run on bench outside the blade. The most important design targets were:

- High structural stiffness
- Low friction of the bearings
- No mechanical play
- Low mass of the unit, especially of the flap

One pair of piezoelectric actuators located at a most forward chordwise position act via tension rods on the flap (see Fig. 5).

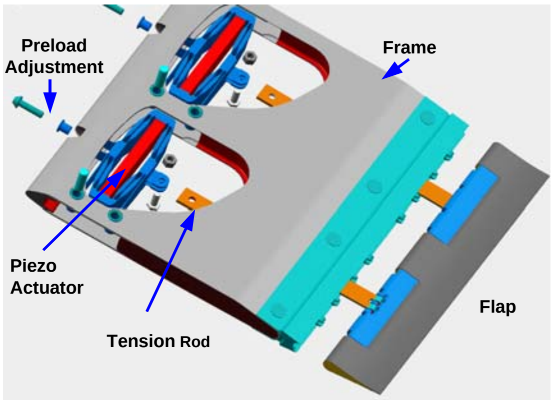

Fig. 5: Flap unit assembly

3.2 Ground Testing

During the development process all main parts such as actuators, housing, flaps, tension rods, data pick-ups, wiring, power supply, and controllers had to undergo subsidiary test procedures. Performance tests under realistic loads demonstrated an acceptable friction level and a life time adequate for an experimental system.

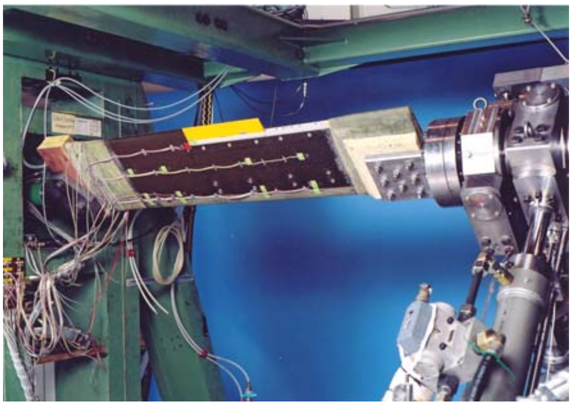

Fig. 6: Blade specimen with active flap during fatigue test

The blade segment containing the flaps was tested in a bending-machine shown in Fig. 6. While the specimen is clamped on the left hand side, it is displaced on the opposite side. It survived the fatigue test with a level far above the flight limit loads. One active flap unit was operated during the tests to check a proper function even when the blade was bent in an extreme manner. A tension load of 107 kN simulating the centrifugal force at nominal rotor speed was superimposed on bending and torsion moments.

Fig. 7: ECD whirl tower with one pair of ADASYS blades

3.3 Whirl Tower Test

The goal of the tests on the whirl tower (see Fig. 7) was to evaluate the aeroelastic properties of the blades such as natural frequencies and inplane damping as well as the capabilities of the active flap units. The flaps were deflected with steady inclination to check the influence on the blade track and blade control forces. During the dynamic tests the flaps were run with frequencies up to the eighth rotor harmonic.

3.4 Ground Testing

A sketch of the system architecture of the BK117 test helicopter is shown in Fig. 8. Besides the rotor with active flaps and the appropriate sensors, a cylindrical compartment is mounted on the rotor hub. It houses the signal conditioning and processing as well as the power distribution to the individual flap units.

For the transfer of the electric power a brushless transducer is installed below the gear box. The electric connection to the hub is established by a coaxial metal tube with a diameter of 8 mm. It contains additionally two plastic fibers which are used for the optical bi-directional data link [6].

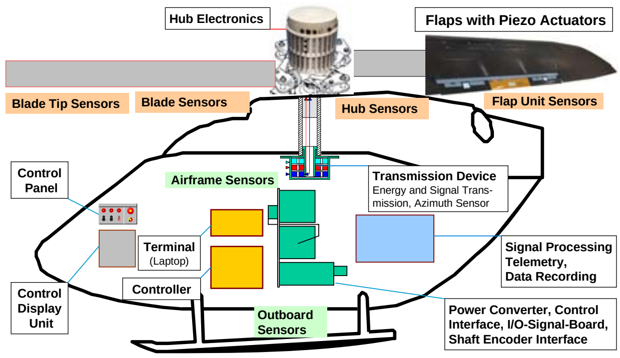

Fig. 8: System architecture of the test helicopter

3.5 Monitoring

Each blade is equipped with sensors monitoring the following parameters:

- Actuator forces and strokes
- Flap angles
- Accelerations at hub and blade tip
- Blade surface pressure (Kulite)
- Structure born sound of vortex impingements
- Temperatures in the flap unit
- Blade bending and torsion moments
- Control forces

Additionally, the airframe contains sensors for accelerations, control loads, control angles and noise.

For BVI detection, a new sensor type based on a piezo film is used. It has the capability to sense the structure born sound in the rotor blade which is generated when a tip vortex hits the blade surface. Because it is applied at the inside of the metal erosion strip the sensor is very robust. The location is at radius station 0.8R.

3.6 IBC Control System

The integration of the IBC computer and the data acquisition system in the fuselage is shown in Fig. 9. This computer is based on a PowerPC provided by dSPACE and allows a direct download of Matlab/Simulink models on the realtime target by using the “Realtime Workshop” (Matlab Toolbox). It offers the possibility to handle all the internal variables of the Matlab/Simulink model by using a software called “ControlDesk” (dSPACE) via a PC and an connected touch screen (Fig. 10). The data acquisition system, which eases the interfacing to other devices like the control computer and the rotor monitoring is located on the top of the rotor. The transmission rate is 100 Mbit/sec and depends on the number of channels (signals) and the required resolution. The transmission frequency between the rotor and the fuselage is 2000 Hz, which is suitable for on-blade noise sensors.

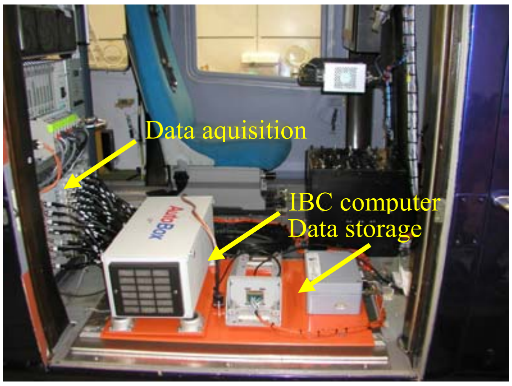

Fig. 9: Integration of the IBC computer and the data acquisition system into the helicopter

Fig. 10: Touch screen with the control panel

3.7 Failure analysis and EMC

The system is completely independent from the primary flight control and thus it is not a flight safety critical item. In case of mal function or loss of electric power of the actuation system, an uncomfortable vibration level may appear but it will not influence the controllability and safety of the helicopter. The additional electric equipment runs the risk to encounter EMC problems in the helicopter. On board are a brushless electric power transducer as well as some switching amplifiers and computers for controlling and data transmission. Low level voltage of the data acquisition has to be handled in the neighborhood of high voltage with steep slew rates. Therefore, high emphasis is given to these effects and thorough tests were run.

3.8 Flight Testing

After securing a save operation of the aircraft on ground which includes the balancing of the rotor and checking of ground resonance stability the system was activated the first time. The helicopter became airborne with some hover flights, followed by air resonance tests and checks of the handling qualities. Although blade pendulum absorbers or other vibration suppression means were not installed the vibration level was rated acceptable by the crew. The official first flight of a helicopter with active trailing edge flaps took place in September 2005. The airborne demonstrator is depicted in Fig. 11. A brief overview of the conducted flight tests is listed in Table 3 showing the objectives and a short summary of the results.

Fig. 11: First flight of a the BK117 S7045 with active trailing edge flaps

4 Hub Load Control Concept

Individual blade control is an efficient means for reducing annoying rotor-induced vibrations at the first blade-number harmonic frequency (4/rev for a four-bladed rotor). Closed-loop flight tests on the BO105 S1 have shown that both vibratory hub loads and airframe vibrations at 4/rev are well controllable by IBC pitch angles in the range of ±1.1deg [4]. This proven control concept has now to be adapted to the new test bed for vibration reduction. The installed disturbance rejection controller is discussed in some detail in the following sections, see also [7].

Tabel.3: Recent activities using individual blade control (IBC) on the BK117 helicopter

Date of Flight	Duration	Objective	Result
08.09.05	0:15	Official first flight of the demonstrator with trailing edge flaps	Demonstration of test bed in flight
05.10.05	2:10	Controllability tests for automatic track control	Controllability of track by static flap deflections demonstrated
26.10.05	1:20	First open loop vibration control investigation	Clear response of the vibration chain due to n/rev actuation achieved
15.10.05	1:25	Open and closed loop noise control	Relationship between onboard microphones and ground microphones checked
21.02.06	1:10	Advanced open loop vibration control investigation	Hub loads reduction with fixed system controller output (4/rev, collective, longitudinal and lateral) established
04.05.06	0:39	Closed loop vibration control in level flight conditions	Significant reduction of vibrations in level flight (30 up to 110kts) and rpm range @ 100kts obtained
11.05.06	0:51	Closed loop vibration control in manoeuvre flight	Significant reduction of vibrations at all flight conditions demonstrated

4.1 Robust Disturbance Rejection Control

The selected control concept has the aim to eliminate the 4/rev hub force and moment excitations. In principal there are three forces (Fx, Fy, Fz) and three moments (Mx, My, Mz), which may excite the airframe. The limited number of IBC control variables restricts the design of disturbance rejection controllers. For the BK117 demonstrator the same actuation channels (collective, longitudinal and lateral) were selected for vibration control as for the BO105. The following targets are chosen as feedback for disturbance rejection control:

Roll moment: Mx = 0 at 4/rev
Pitch moment: My = 0 at 4/rev
Vertical force: Fz = 0 at 4/rev

Robust disturbance rejection control of these three outputs leads to the implementation of dynamic compensators in the feedback loop. The compensators are derived from the internal model principle and are realised as notch filters (design frequency 4/rev in the fixed/airframe system) for modelling the sinusoidal nature of the disturbances at the blade passage frequency. The notch filters represent undamped oscillators introducing transmission zeros into the closed loop system thereby enforcing in principle the elimination of the controlled output variables at 4/rev. In order to use the entire potential of the dynamic compensators, the notch filters take into account variable rotor speeds by online adaptation. Fig. 12 displays the final structure of the vibration controller [4] using the advantages of output feedback.

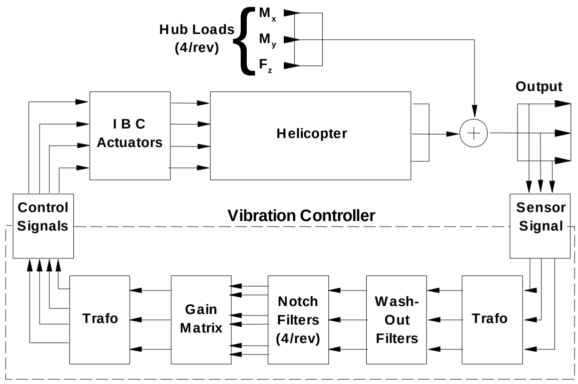

Fig. 12: Feedback loop for 4/rev hub load disturbance rejection (fixed system)

The core of the vibration controller is formulated in the fixed system being on the one hand a very natural approach for airframe vibration control and significantly simplifying on the other hand controller design by focusing on one discrete design frequency (blade passage frequency). The transformation formulas are based on the usage of multi-blade coordinates for blade sensor and actuation control data. The application of multi-blade coordinates additionally offers the opportunity to approximate the linear time periodic equation system for vibration prediction by a linear time invariant equation system without neglecting major periodic characteristics.

The vibration controller consists of two dynamic components – washout filters for pre-conditioning the sensor signals and notch filters acting as servo compensators – and of the static gain matrix. The determination of the gain matrix elements is essential for controller performance and stability. Due to the internal structure of the vibration controller, 18 scalar elements define the gain matrix of three rows and six columns. From a theoretical point of view, advanced controller design procedures like optimal output feedback (linear quadratic output feedback) allow the calculation of the gain matrix.

In [7] a semi-empirical procedure has been developed for the determination of the 3x6 gain matrix based on flight test results. This method requires the inflight measurement of the open loop system transfer functions at 4/rev. The open loop system transfer matrix is defined in the Laplace domain by:

$$y_{Hub} = G(s) \cdot u_{IBC} + d_{Hub}$$

with

$$u_{IBC} = \left(\theta_{coll}, \theta_{long}, \theta_{lat}\right)^T$$

$$y_{Hub} = \left(F_z, M_x, M_y\right)^T$$

$$d_{Hub} = \left(F_z, M_x, M_y\right)^T_{Hub}$$

$$\text{and } G = \begin{bmatrix} g_{coll \to Fz} & g_{long \to Fz} & g_{lat \to Fz} \\ g_{coll \to Mx} & g_{long \to Mx} & g_{lat \to Mx} \\ g_{coll \to My} & g_{long \to My} & g_{lat \to My} \end{bmatrix}.$$

The equation uses standard notations, i.e.

u: inputs,
y: output,
d: disturbance and
G: transfer function.

The matrix elements must be determined at s = i(4Ω) by appropriate sinusoidal IBC pitch control inputs. Such measurements were conducted for the BK117 flight demonstrator at level flight conditions:

Flight speed: 100 kts
IBC inputs: 3 deg flap angle at variable phase
Rotor speed: 100% (Ω=6.39 Hz)

The results will be presented later in chapter 5.

4.2 Feedback Signals and Sensors

The required 4/rev hub loads in the fixed system for the applied disturbance rejection controller are measured indirectly. Shaft bending moments are appropriate for the estimation of fixed system hub roll and pitch moments (Mx, My) in conjunction with coordinate transformations. Flap and lead-lag bending moments at the hub arms (blade attachment) are appropriate to estimate the hub forces in vertical and chordwise direction, respectively. Thus the four applied strain gages for the flap moments enable the direct calculation of the vertical force by applying modal factors for the conversion of the bending moments into the vertical hub force (Fz). The lead-lag bending moments can be used to determine estimates for the inplane hub forces (Fx, Fy). These two forces are not yet used by the flight tested vibration controller.

4.3 Vibration Controller Realisation

The general development of control algorithms can be subdivided into three activities

- System modelling and identification
- Controller design and simulation
- Realtime code generation

Fig. 13 shows the general concept of the established "development chain". This was successfully applied together with vibration control concept tested on the BO105 helicopter.

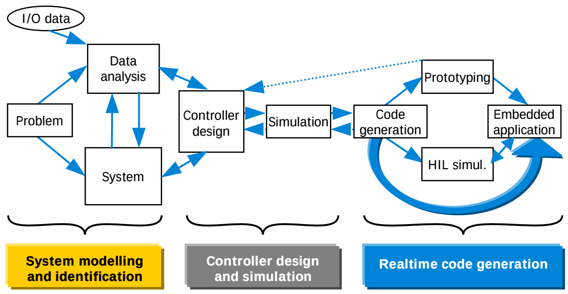

Fig. 13: Realtime controller realisation

The system modelling and identification is based on comprehensive rotor models (e.g. CAMRAD II code) and Matlab scripts for open loop system transfer function identification from flight measurements.

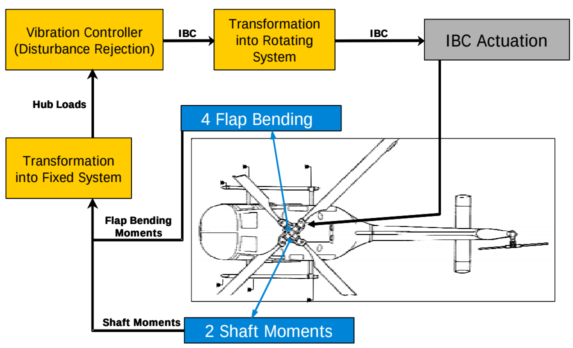

Fig. 14: Schematic view of the vibration control system

The **design and simulation** of the selected vibration controller has been carried out by various simulations and tests using Matlab/Simulink. The applied computer tools have allowed a very fast and easy adaptation of the existing vibration controller for blade root actuation. The general structure of the vibration controller is presented in Fig. 14. As described above 4 flap bending moments and 2 shaft bending moments are used for the required feedback signals.

The **realtime code generation** is performed by using well proven, modern software tools from Mathworks (RTWorkshop) and dSPACE (RTInterface). The interaction of these two packages allows a direct compilation of the Simulink models with all its components required for embedded applications. The dSPACE environment provides all the tools needed for automatic code generation and realtime simulation (hardware-in-the-loop simulation). All blocks for data acquisition and feedback outputs (D/A-converter etc.) are presented as a blockset for Simulink.

Once the model is tested and the input and output signals are defined, a simple key combination allows the download of the generated controller code from the host to the realtime computer. After this download a second tool from dSPACE, the so called "Control Desk", enables the possibilities of monitoring or changing gain, notch dampings and any other variables during flight testing. The interaction with the realtime controller is realised by using a touch-screen (see Fig. 15).

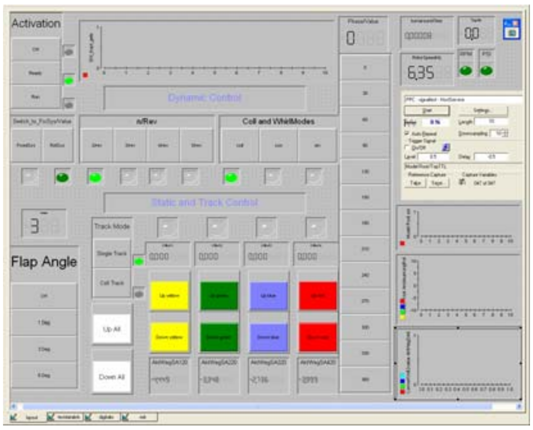

Fig. 15: Touch screen with the Control Desk surface

5 Open Loop Investigations

Special open loop flight tests on the BK117 S7045 were performed prior to the implementation of the hub load vibration controller (see table 3). The performed measurements are aimed at testing the implemented hub load sensor system and at establishing reliable 4/rev frequency response data of the plant (rotor system) for control purposes.

5.1 Transfer Function Identification

The establishment of reliable 4/rev transfer functions is a crucial task for later flight testing of the disturbance rejection controller. Test flights have been performed with collective, longitudinal and lateral IBC inputs. During these tests the three hub loads Fz, Mx and My were recorded as outputs.

Fig. 16 shows in a representative manner for collective flap actuation with a control voltage of 4 Volt (40% output of the IBC computer)

$$\left(u_{IBC}\right)_{coll} = 4.0 Volt \cdot \cos\left(4\Omega t - \varphi_{IBC}\right)$$

the dependence of the 4/rev hub force (after the washout filters) vs. the assigned IBC phase @ 100kts. In this case a clear relationship between input and output can be noted

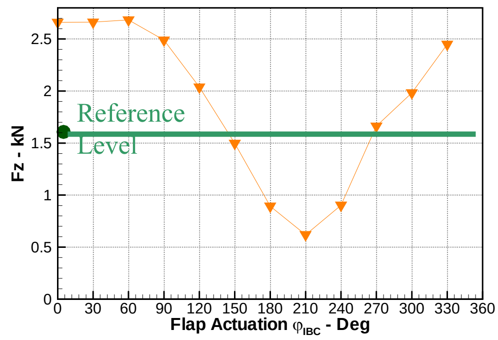

Fig. 16: Vertical hub force in dependence of the IBC phase in level flight (100kts)

Assuming a linear relationship between the inputs and the outputs, the transfer functions were defined in section 6.1. The evaluation of the 3x6 complex valued transfer functions at 4/rev and the three disturbances corresponding to the zero input case can be facilitated by standard least square identification techniques [8]. For the controller layout the 4/rev transfer matrix elements are of special interest. These elements are collected in the following matrix:

$$G = \begin{bmatrix} 275.7 - 73.9i & 15.4 - 7.9i & 88.4 - 46.0i \\ -13.4 + 21.9i & -30.8 - 39.8i & -47.8 + 19.3i \\ 40.5 - 16.7i & -45.2 + 21.9i & 59.1 + 9.9i \end{bmatrix}$$

The units are N/Volt for the force elements (top row) and Nm/Volt for the moment elements (bottom two rows).

For further evaluation the transfer functions are applied for determine IBC-induced 4/rev hub loads. Using the elements of the first row, assuming collective inputs with 40% amplitude and phase angles between (0÷330) deg in steps of 30 deg these IBC-induced 4/rev hub loads are elaborated and presented in the following three figures:

Fig. 17: 4/rev vertical force (Fz)

Fig. 18: 4/rev roll moment (Mx)

Fig. 19: 4/rev pitch moment (My).

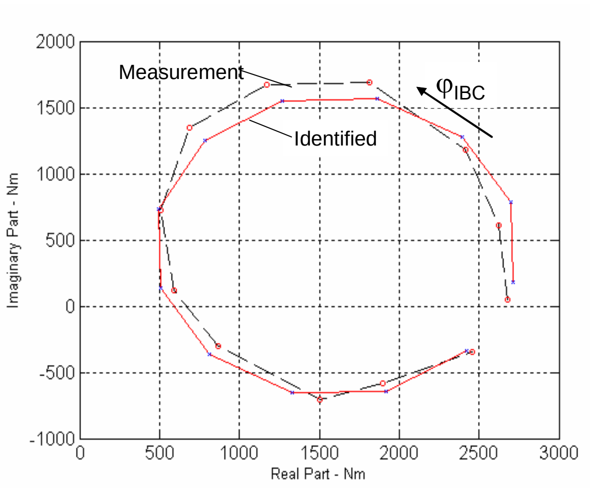

Fig. 17: Comparison of 4/rev vertical forces (Fz) at 100 kts (identified vs. measurement)

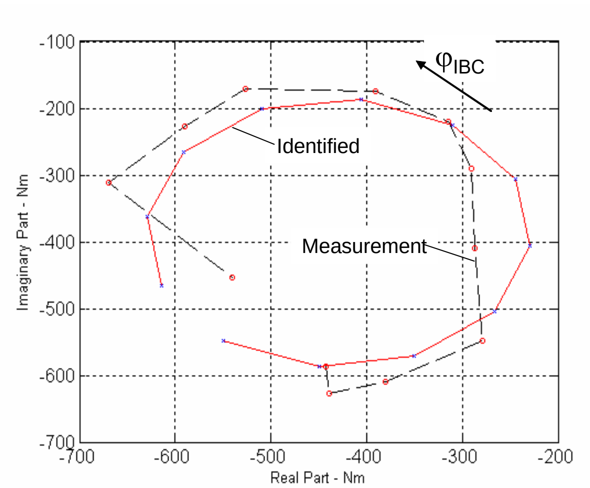

Fig. 18: Comparison of 4/rev roll moments (Mx) at l00 kts (identified vs. measurement)

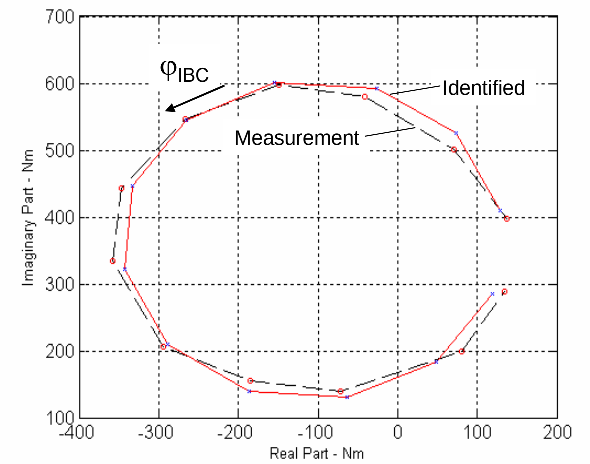

Fig. 19**:** Comparison of 4/rev pitch moments (My) at 100 kts (identified vs. measurement)

The agreement between measurement and identified model is good. The identified model matches well the test data. Similar results are obtained for longitudinal and lateral IBC pitch inputs. The identified transfer matrix was used for the setup of the gain matrix of the disturbance rejection controller for the BK117 flight demonstrator [7].

6 Closed Loop Investigations

As worked out, the feedback gains are determined by using the 4/rev system transfer matrix elements from section 5.1 with the possibility of inflight adjustments for each control channel. The flight tests were aimed on testing the complete collective and cyclic disturbance rejection control for Fz, Mx, and My, simultaneously. Flight tests will be continued with an advanced controller and optimized parameters.

6.1 Controlled Hub Loads and Vibrations

The focal point of the flight tests was to demonstrate the same good performance and vibration reduction as achieved with the BO105 with blade root actuation.

Level Flight: Tests at level flight speeds from 50 to 110 KIAS and rotor rotational speed variations (98÷102)% at 100kts were conducted in order to explore the performance of the hub load vibration controller with notch frequency adaptation. The 4/rev hub loads with and without IBC are plotted in Fig. 20 and in Fig. 21. For both parameter variations pronounced reductions of the 4/rev hub loads could be achieved. During level flight conditions (Fig. 20) improvements between 50% and 90% could be shown. The implemented automatic rotor speed adaptation of the dynamic compensator works well, (Fig. 21). The vibration reduction capability of the controller is nearly independent from rotor speed changes.

The 4/rev gearbox vibrations are presented in Fig. 22. The vibration levels with IBC engaged are reduced in all cases. Remarkable strong improvements are obtained in longitudinal and lateral direction. For example at 110kts level flight the lateral gearbox accelerations are reduced from about 0.8g down to less then 0.2g. The vertical cabin vibrations (Fig. 23) are lowered to values of about 0.05g. The remaining accelerations may be explained by the not-controlled lateral hub forces. Overall the achieved low vibration levels were confirmed by the flight test crew's excellent rating.

Climb and Descent: The vibration reduction performance of the IBC controller was tested next for climb and descent rates of ±1500 ft/min (flight speeds of 65kts) providing further insight in the robustness of the controller. The 4/rev hub excitations and cabin response data are plotted in Fig. 24 and Fig. 25, respectively.

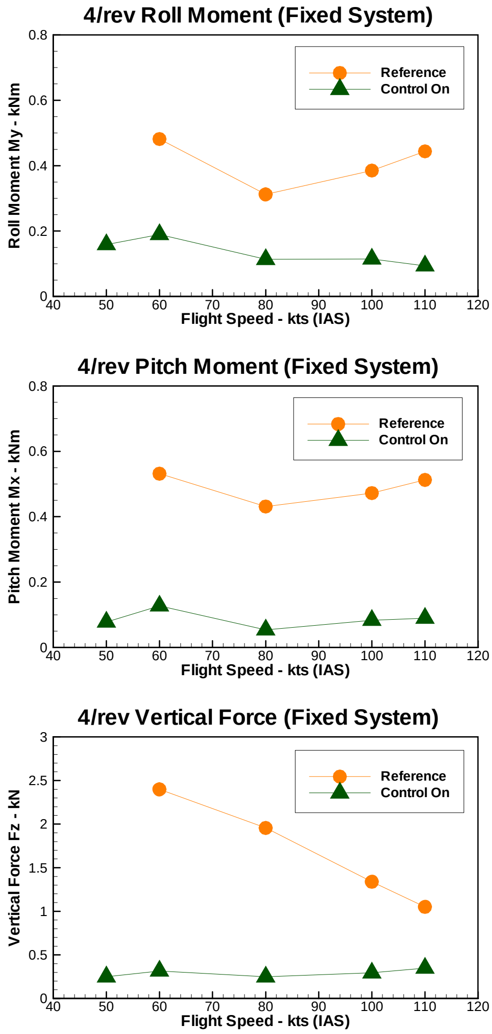

Fig. 20: Controlled hub loads vs. flight speed (100% rotor speed)

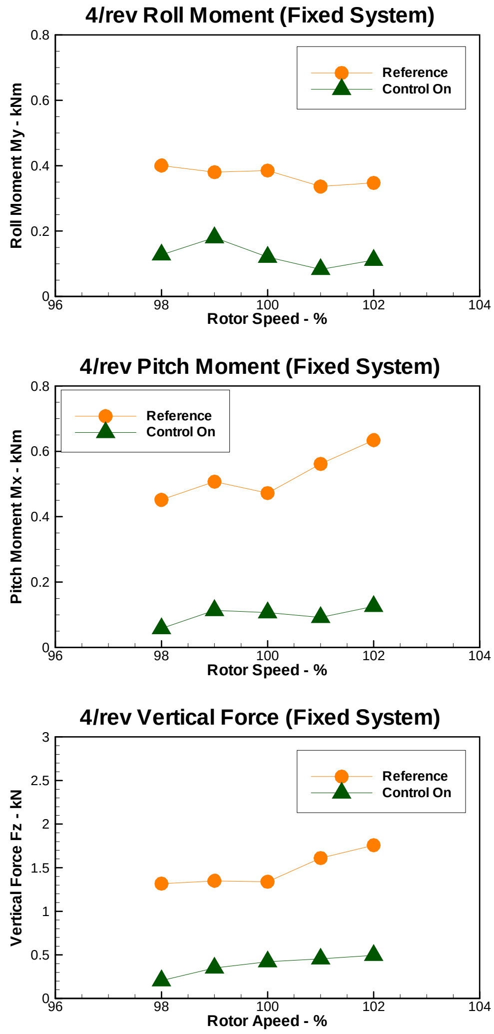

Fig. 21: Controlled hub loads vs. rotor speed (100kts flight speed)

The results show that the controller efficiently rejects the vibratory hub loads (Mx, My, Fz) and reduces the cabin accelerations below 0.1g.

Manoeuvre flight: The investigations are concentrated on left and right turns at 80kts with load factors up to 1.6g (50° bank angle). The measured 4/rev hub loads are presented in Fig. 26. Once again the hub load controller shows an excellent performance and reduces all three controlled loads to low values. The corresponding cabin vibrations show the expected low acceleration levels. For example, the 4/rev cabin vibrations for the 1.6g right turn at 80kts are 0.05g in x-direction and 0.06g in z-direction with engaged IBC controller. Time constraints have yet prevented flight testing of more advanced manoeuvres for demonstration the whole benefits of the applied control concept.

6.2 Influence on Uncontrolled Loads

During flight testing the inplane and out of plane blade attachment bending moments were recorded. It is well known from hingeless rotors that the out of plane vibratory loads are dominating the vibration excitation. The tested disturbance rejection controller is aimed for cancellation of flap bending induced rotor loads. Nevertheless the inplane bending is of interest. The rotor harmonic inplane bending moments contribute to the fixed system vibration excitations at 4/rev as follows

- 3/rev, 5/rev lead-lag bending excitations causes longitudinal and lateral hub forces (Fx, Fy)
- 4/rev lead-lag bending excitation results in yaw (torsional) hub moments (Mz)

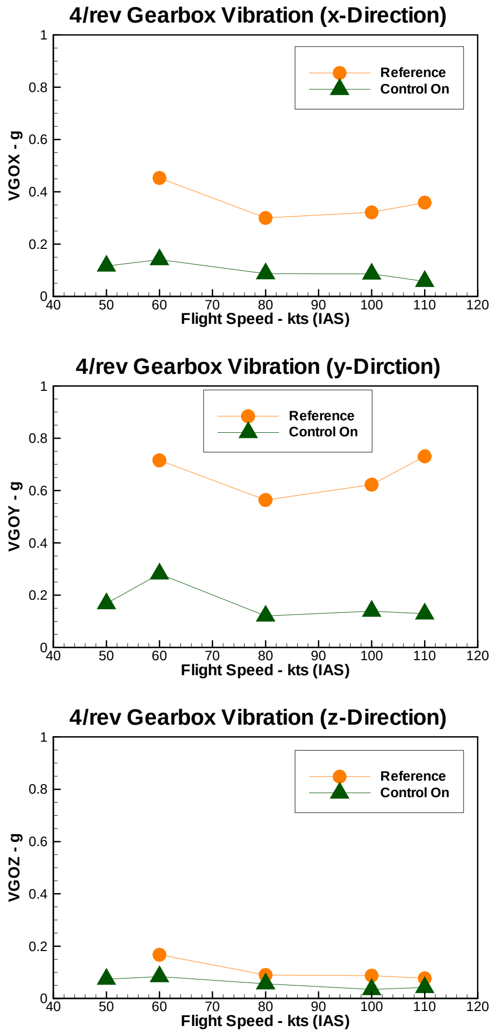

Fig. 22**:** 4/rev gearbox vibration vs. flight speed (100% rotor speed)

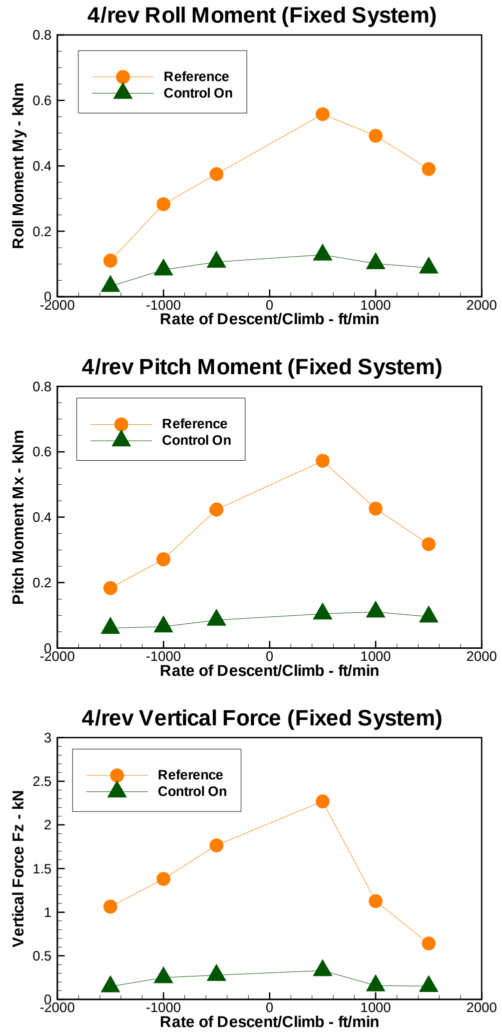

Fig 24: 4/rev hub loads vs. rate of climb/descent at 65 kts

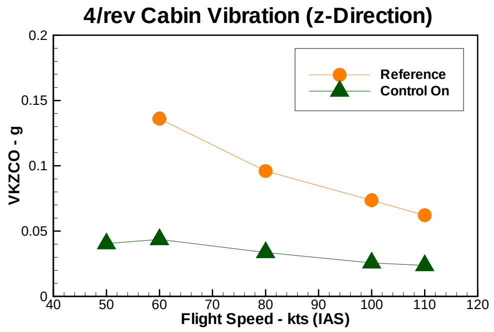

Fig. 23: 4/rev cabin vibration (z-direction) vs. flight speed (100% rotor speed)

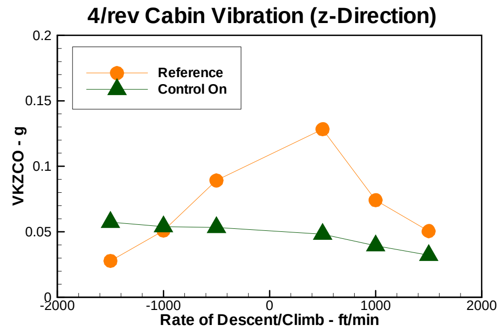

Fig.25:4/rev cabin vibration (z-dirction) vs. rate of climb/descent at 65 kts

The rotor harmonic moment amplitudes of the lead-lag bending moments at 100 kts level flight is shown in Fig. 27 (0.172m radius).

Obviously, the inplane blade bending loads are weakly affected by the actuation which may be explained by the applied low control gains.

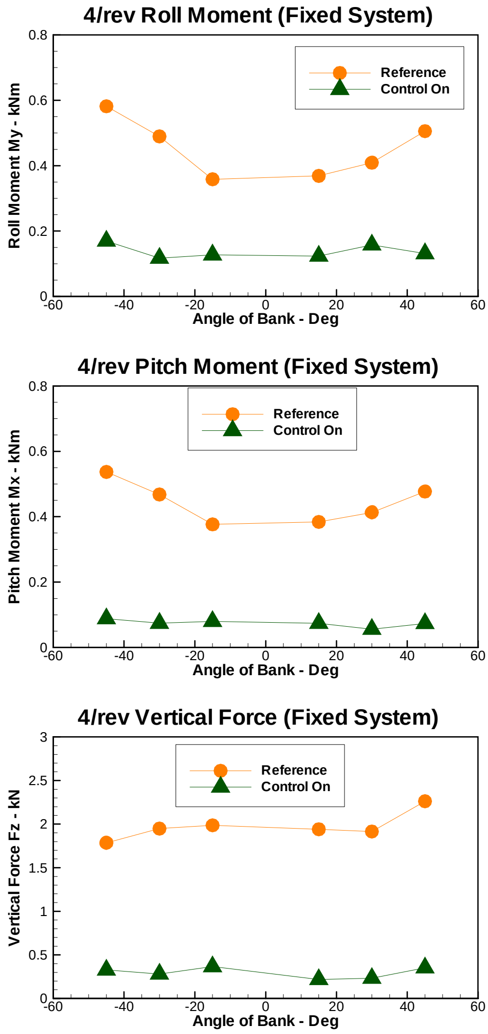

Fig.26: 4/rev hub loads in manoeuvre flight conditions at 80 kts

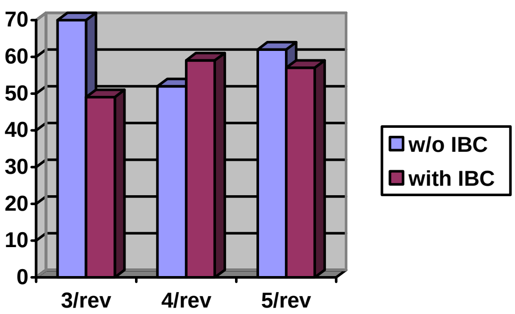

Fig. 27: Lead –lag amplitudes (M_ζ – Nm) with and without IBC at 100kts level flight

7 Outlook

The application of IBC technology on production helicopters is the common goal of various research programs world-wide, see [9]. For this approach it is necessary to minimize the weight and the volume of all the electrical and mechanical devices. For the next generation of active rotor an improved concept of data acquisition will be available. Fig. 28 shows a concept, which uses existing of-the-shelf hardware. The complete power distribution and acquisition unit will fit under a typical hub cap. Actually the system is tested in the laboratory [10]. Simultaneous noise and vibration control is prepared for demonstration of the outstanding capabilities of IBC technology as well as other applications.

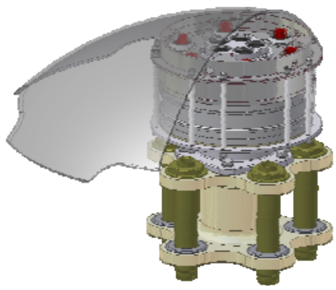

Fig. 28: Hub compartment beneath the hub cap

8 Conclusion

Robust disturbance rejection control for airframe vibration reduction was adapted from the BO105 with blade root actuation to the BK117 demonstrator with trailing edge flaps. The flight tested hub load controller uses output feedback in the time domain and is aimed for cancellation of blade number harmonics without gain scheduling at 4/rev at all evaluated flight conditions. The expected reduction of 4/rev vibrations in the whole aircraft was confirmed within few flight tests with remarkable success. Further flight tests of the controller/sensor system are envisaged for controller optimisation. Generally the following conclusions can be drawn based on the experience of two IBC systems with different actuation:

- IBC technology is well suited to apply advanced vibration control methodology for helicopters.
- Vibration control in the time domain has a great potential and may be applied for both hub load and airframe response reduction or minimisation; this includes various modern optimal and alternative adaptive control concepts, see Ref. [11-14].
- Dynamic feedback compensators with rotor speed adaptation are efficient and are easy to install by modern digital controller hardware.
- Efficient IBC vibration control schemes require reliable theoretical models and/or experimental plant data.
- The IBC system can be expended for simultaneous vibration reduction and rotor stabilization, see [15]

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