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ADVANCED VIBRATION REDUCTION BY IBC TECHNOLOGY

by

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The capability of individual blade control (IBC) for helicopter vibration reduction has been demonstrated in the past by various flight test campaigns and related theoretical investigations. Such a system, manufactured by ZF Luftfahrttechnik (ZFL), is installed on a BO105 helicopter and was already successfully tested in open loop configuration by EUROCOPTER DEUTSCHLAND GmbH (ECD). The test results show that the relationship between IBC input and generated hub loads and accelerations is very sensitive with respect to test conditions (e.g. flight/wind speed). This sensitivity has consequently led to the demand for a closed loop system by feeding back hub loads or vibrations as error signals. The improvement in micro controller technology offers the possibility to implement advanced time domain algorithms for vibration control under all flight conditions.

This paper presents the recent activities on the realization and flight testing of a closed loop control system on the BO105 IBC demonstrator focused on hub load suppression. Special emphasis is given on the required equipment and the applied algorithms.

The demonstrator is equipped with proven electro-hydraulic blade pitch actuators with adequate authority for vibration reduction. This actuation system is controlled by an embedded digital computer from dSPACE in combination with a new high performance signal processing equipment for the data transfer between the rotating and nonrotating system. Moreover, special interfaces like a modern touch screen are provided for the communication between the flight test engineer and the realtime computer system. This interface is used for direct monitoring of sensor signals and controller behaviour in realtime. This new system allows the flight test engineer to handle the controller gains and system matrices during flight testing. For vibratory hub load control a complex sensor system in the rotating frame is installed. The vibratory 4/rev hub load control is based on an output feedback controller for disturbance rejection in the time domain. The core of the controller is formulated in the fixed system which is a very natural approach for airframe vibration control and is significantly simplifying the controller design by focusing on one discrete excitation frequency (blade passage frequency).

The presented controller is suitable for general IBC systems including the piezo-active trailing edge flap which was recently tested with success on the whirl tower.

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
q	IBC actuation angle
j	IBC phase

Acronyms

BVI	Blade vortex interaction
IBC	Individual Blade Control

1 Introduction

Eurocopter Deutschland (ECD) has long term experience in the investigation and development of individual blade control (IBC) technology. In the year 1990 the first IBC flight tests were started on the BO105 S1 helicopter (see Fig.1), using the most straightforward concept of blade root actuation. For this concept the conventional pitch links must be substituted by electrio-hydraulic actuators, which are provided by ZF Luftfahrttechnik (ZFL). In the last years the active trailing edge flap concept has gained much interest for future IBC systems. The BK117 S7045 helicopter was recently equipped with piezo-electric trailing edge flaps, developed by EADS Corporate Research Center (CRC) in cooperation with ECD. Both flight demonstrators have a four-bladed hingeless main rotor with similar dynamic layout. Thus valuable research results gained in the past may be applied on both rotorcrafts. A short survey of performed activities on the BO105 IBC demonstrator and of planned activities on ECD's new BK117 IBC demonstrator is given in Tab. 1, which is an updated version presented in Ref. 1.

Tab. 1: Past and planned activities using individual blade control (IBC) on the BO105 / BK117 helicopter

Year	IBC Tests	Actuator Authority	Flight Speed (Wind Speed)	IBC Amplitudes	IBC Harmonics	Objectives	Demonstrator
1990 1991	**First flight tests** Open loop Single-harmonic input	0.25° 0.49°	60/115 kts, 65 kts descent	0.16° 0.40°	3/rev 4/rev 5/rev	Vibration and BVI noise characteristics	**BO105** (Blade Root Actuation)
1993 1994	**Wind tunnel tests, NASA Ames** Open loop Single and multi-harmonic input	3.0°	43 ÷ 190 kts (μ=0.10÷0.45)	max. 2.5°	2/rev ÷ 6/rev	Vibration and BVI noise characteristics, performance at high speed	
1998	**Flight tests with increased authority** Single harmonic input	1.1°	110 kts, 65 kts descent,	0.40°/1.0°	2/rev ÷ 5/rev	BVI noise and vibration characteristics	
2001	**Flight tests with noise controller** Closed loop Phase control	1.1°	65 kts descent	1.0°	2/rev	BVI noise reduction	
2003 2004	**Flight tests with vibration controller** Closed loop Time domain (TD) control	1.1°	60 ÷ 100 kts 65 kts descent 80 kts turns	max. 1.0°	3/rev 4/rev 5/rev	Vibration reduction	
2004	Whirl tower test with active flaps	+6° -8°	-	max. 6°	2÷6/rev	Functionality test	**BK117** (Flap Actuation)
Next	Adaption of all control laws to the new rotorsystem with active flaps	+6° -8°	Hover ÷ 110 kts	max. 6° (Flap)	(2÷6)rev	Simultanious noise and vibration reduction	

Fig. 1: BO105 S1 IBC demonstrator in flight

Individual blade control is well suited to directly modify the excitation forces acting on the rotor blades. Of special interest is the control of the lift distribution on the rotor disk which offers new possibilities to reduce or eliminate vibration and noise, to enlarge the flight envelope and last but not least to improve inflight blade tracking. Based on wind tunnel and flight test experience in the past the practical realisation of these goals requires a sophisticated closed loop control implementation. Principally closed loop control adds the capability to improve the aeromechanical and aeroelastic stability characteristics of the complete system, too. Thus ECD has focused its development at an early stage on closed loop time domain control concepts for IBC system implementation.

Blade-number harmonic airframe vibrations and external rotor noise radiation due to blade vortex interaction (BVI) are still belonging to the most challenging problems of current helicopters. Typical airframe vibration spectra of the BO105 S1 flight demonstrator without special passive or active vibration reduction means are presented in Fig. 2. The dominant first blade-number harmonic vibration amplitudes at 4/rev (28Hz) are obvious in all three axes. The measured 4/rev vibration levels at 60 kts level flight are in the range of (0.1 ÷ 0.18)g.

The simultaneous control of vibration and noise is one of the key objectives of ECD's current IBC research efforts. For the four-bladed BO105 main rotor an appropriate IBC-based vibration and noise control concept is elaborated in Ref. 2, assigning different multi-blade pitch control modes for both tasks:

- Vibration control by collective, longitudinal and lateral IBC inputs
- Noise control by differential IBC inputs

The separation of noise and vibration control axes has simplified the implementation and testing of both controllers on the BO105 flight demonstrator.

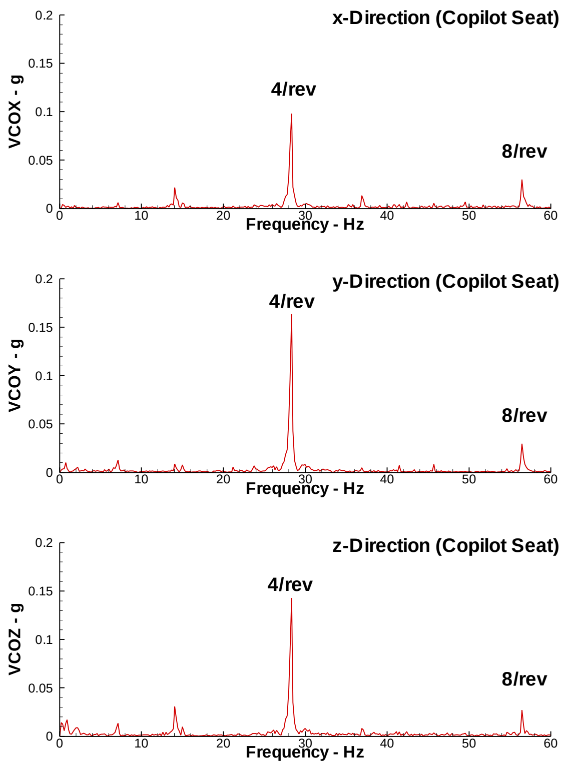

Fig. 2 BO105 S1 vibrations in level flight @ 60 kts

The BVI noise controller concept and various flight test results are outlined in Ref. 1,3. A remarkable 6dB noise reduction in descent flights was achieved by using closed loop 2/rev (differential) IBC pitch inputs with amplitude and phase adjustments. The theoretical background and the design of the vibration controller is outlined in Ref. 2. The concept applies output feedback control and standard disturbance rejection theory, uses collective, longitudinal and lateral IBC pitch inputs and vibratory hub loads as feedback signals. The inflight testing of the vibration controller in both open loop and closed loop operation was recently conducted on the BO105 IBC demonstrator with noteworthy success.

In this paper more details are presented about this vibration controller and about the flight test measurements on the BO105 S1. The experimental system setup is reviewed and the applied control concept and hardware realisation are elaborated. Subsequent discussions are related to open loop flight testing and transfer function measurements for a semi-empirical controller setup. Afterwards the special features and advantages of this controller concept are discussed with emphasis on cruise and manoeuvre flight conditions. In addition, the efficiency of the controller is demonstrated by a number of flight tests. Finally an outlook is given on forthcoming activities with actively controlled flaps on the BK117 S7045.

2 Experimental System

In order to prepare the BO105 flight demonstrator for the actual open and closed loop IBC test campaign, a lot of new systems had to be tested and installed into the helicopter. Key points were:

- Integration of a new and faster embedded control computer
- Application of new feedback sensors on the rotor hub
- Integration of a new fast datalink between the rotating and the nonrotating system provided by the DLR (Deutsches Zentrum für Luft- und Raumfahrt)
- Installation of a modern touch screen on the copilot side for online adaptation of control laws during flight

The complete experimental system is described in Ref. 1. A short review and some additional informations concerning the new installed components are given below.

2.1 IBC Actuation System

The actuation system can be divided into two parts:

- The hydraulic pump and the electronic equipment installed in the helicopter fuselage
- The hydraulic actuators with their sensors in the rotating system.

The hydraulic power is distributed to the four hydraulic actuators using a hydraulic slip ring for the transfer from the fuselage to the rotating system. In addition the corresponding electrical signals are transmitted by an electrical slip ring.

A central element of the blade root control system are the hydraulically powered actuators. The actuators replace the conventional push rods between the pitch horn and the swashplate and thus become part of the primary flight control system, see Fig. 3.

Fig. 3: Servo-hydraulic actuator

The working piston stroke can be controlled for each actuator separately within the range of ± 1.1deg blade pitch angle. Each actuator is equipped with a local position feedback loop ("inner loop"). The actual piston position is measured by a position transducer (LVDT) inside each actuator. The essential actuator data are listed in Tab. 2. For flight testing of the IBC system an appropriate safety concept was developed, see Ref. 1.

Tab. 2: Actuator data

piston stroke	± 3.2	mm
max. piston velocity @ zero load	0.39	m/s
bandwidth	70	Hz
actuator length	289	mm
piston area	2.97	cm^2
system pressure	207	bar
max. dynamic load (hydr. limit)	3000	N
max. static load (hydr. limit)	6100	N
min. locking force	2500	N
system mass	2.5	kg

2.2 IBC Control System

The integration of the IBC computer and the data acquisition system into the fuselage is shown in Fig. 4. 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). Furthermore this computer offers the possibility to handle all the internal variables of the Matlab/Simulink model by using a software called "ControlDesk" (dSPACE) over a PC and an attached touch screen. This touch screen with control surface is presented in Fig. 5. The expandable design of the data acquisition system, which eases the interfacing to other devices like the control computer and the rotor measurement equipment, is located on the top of the rotor above the hydraulic and electric slip rings. The transmission rate is about 10Mbit/sec and depends on the number of channels (signals) and the required resolution.

3 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). Flight test measurements 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, which is compliant with the piston stroke data from Tab. 2. For vibration reduction on the BO105 flight demonstrator a hub load disturbance rejection controller is installed, which is discussed in some detail in the following sections.

Fig. 4 Integration of the IBC computer and the data acquisition system into the helicopter

Fig. 5 Touch screen with the control surface

3.1 Robust Disturbance Rejection Control

The selected hub load control concept has the aim to eliminate the main 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 structure, see Fig. 6. The limited number of IBC control variables is a major restriction in the design of disturbance rejection controllers. For the BO105 demonstrator there are three pitch actuation channels (collective, longitudinal and lateral) but six disturbances. Based on flight experience with the BO105 helicopter the following hub excitations are selected as outputs 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 by the available three IBC pitch controls requires 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.

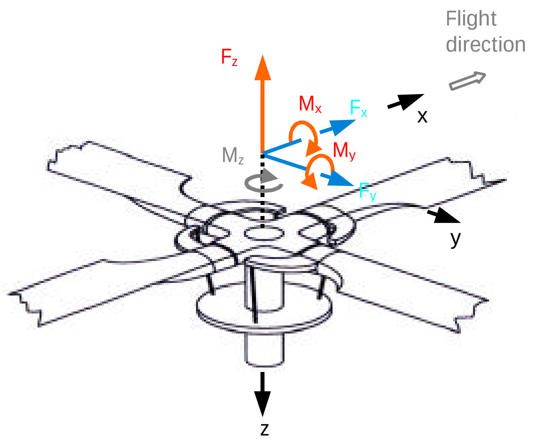

Fig. 6: Hub loads for feedback control

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 varying rotor speeds by online adaptation of the notch frequency tuning. Fig. 7 displays the final structure of the vibration controller (Ref. 1) using the advantages of output feedback.

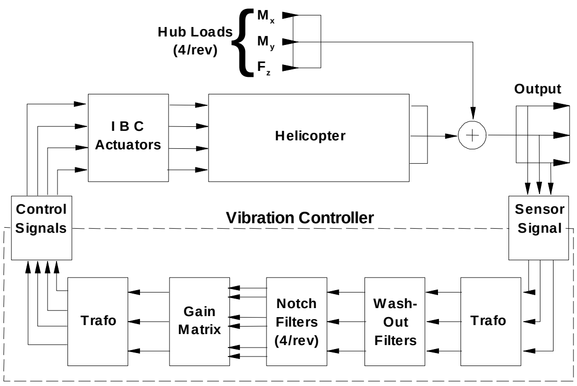

Fig. 7: Feedback loop for 4/rev hub load disturbance rejection (fixed system)

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 independent 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 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. Nevertheless, procedures of this kind require an appropriate theoretical model of the plant representing helicopter dynamics including actuators and vibration sensors.

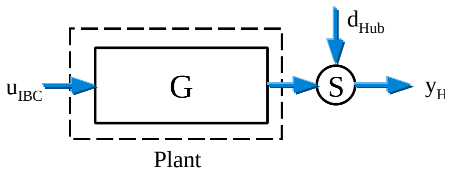

Fig. 8 Vibratory hub load control by IBC

In Ref. 2 a semi-empircial procedure has been developed for the determination of the 3x6 gain matrix. This method requires the inflight measurement of the open loop system transfer functions at 4/rev. According to Fig. 8, the open loop system transfer matrix is defined in the Laplace domain by:

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

with

$$u_{IBC} = col(q_{coll}, q_{long}, q_{lat})$$
$$y_{Hub} = col(F_z, M_x, M_y)$$
$$d_{Hub} = col(F_z, M_x, M_y)_{Hub}$$

and

$$G = \begin{bmatrix} coll \rightarrow Fz & long \rightarrow Fz & lat \rightarrow Fz \\ coll \rightarrow Mx & long \rightarrow Mx & lat \rightarrow Mx \\ coll \rightarrow My & long \rightarrow My & lat \rightarrow My \end{bmatrix}.$$

The formula uses standard notations, i.e.

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

The matrix elements must be determined at s = i(4O) by appropriate sinusoidal IBC pitch control inputs. Such measurements were conducted for the BO105 flight demonstrator at level flight conditions:

Flight speed: 100 kts
IBC inputs: 0.44 deg at variable phase
Rotor speed: 100% (O=7.07 Hz)

The result will be presented later in chapter 4.

3.2 Feedback Signals and Sensors

The required 4/rev hub loads (fixed system) cannot be measured directly, therefore other sensor signals have been chosen for the realisation of the vibration controller. Theoretical and experimental investigations have shown that a reasonable concept for the computation of the hub loads is the use of strain gages for bending moment measurements in the rotating system (see Fig. 8).

Shaft bending moments in two directions are appropriate for the estimation of fixed system hub roll and pitch moments (Mx, My) in conjunction with kinematic coordinate transformations.

Flap and lead-lag bending moments at the hub arms (blade attachment) are appropriate to estimate the hub forces in vertical and inplane 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 forces are not yet used by the flight tested vibration controller..

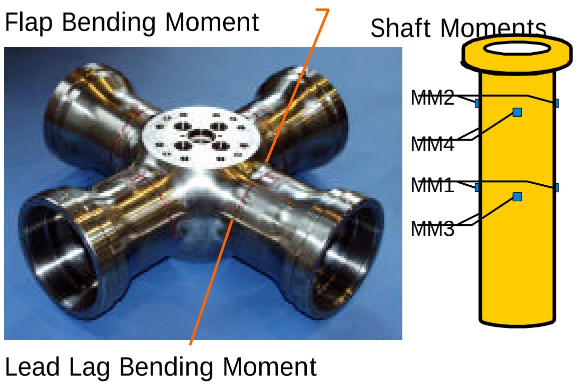

Fig 8: Sensors in the rotating system

3.3 Vibration Controller Realisation

The realisation of the vibration controller for the BO105 flight demonstrator is based on new software tools and hardware components. The general development of control algorithms can be subdivided into three activities

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

Fig. 9 shows the general concept of the applied "development-chain" provided by Mathworks and dSPACE.

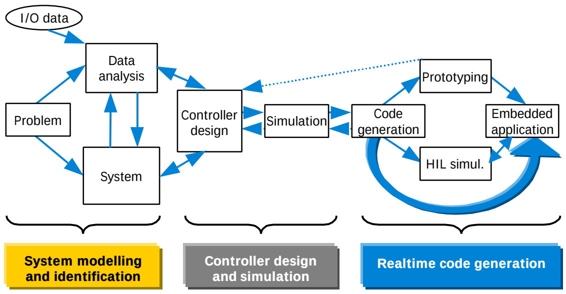

Fig. 9: Realtime controller realisation

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.

The ***design and simulation*** of the selected vibration controller has been carried out by various simulations and tests, using Matlab/Simulink. The general structure of the vibration controller is presented in Fig. 10. As described above 4 flap bending moments and 4 shaft bending moments are used for the required feedback signals (vertical hub force and roll/pitch hub moments in the fixed system).

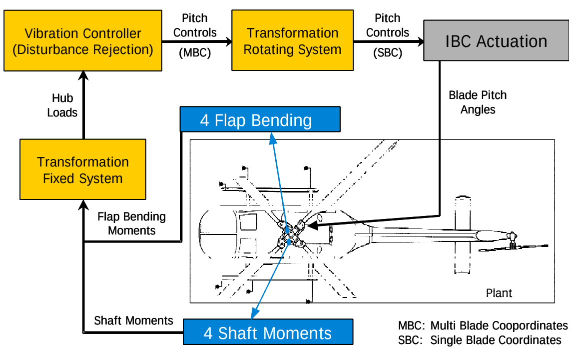

Fig. 10 Schematic view of the vibration control system

A detailed simulation model of the complete hub load vibration controller including vibratory feedback sensor preprocessing and fixed system transformation, washout filters, dynamic compensators and controller gains, control output evaluations, subsequent inverse multi-blade transformation of the IBC pitch controls into single blade actuation control commands and software limiters were realised by using Matlab/Simulink. This model is presented in the appendix. The controller model enables sophisticated closed loop aeroservoelastic simulations of the rotor/helicopter vibration control system. (Appropriate multi-blade rotor models for the BO105 with IBC pitch control are established in Ref. 1 with the Camrad II code.)

Fig. 11 demonstrates the behaviour of the presented vibration controller by closing the feedback of the vibration control loop. The functionality of the vibration controller under perfect conditions (without noise) is clearly visible due to the hub load attenuation within a few rotor revolutions. Nevertheless, spikes in the control system are generated by the immediate activation of the feedback loop leading to excessive hub loads during the first revolution of active control. Therefore, a ramp function will be used in conjunction with the gain matrix in order to avoid overloading while flight testing.

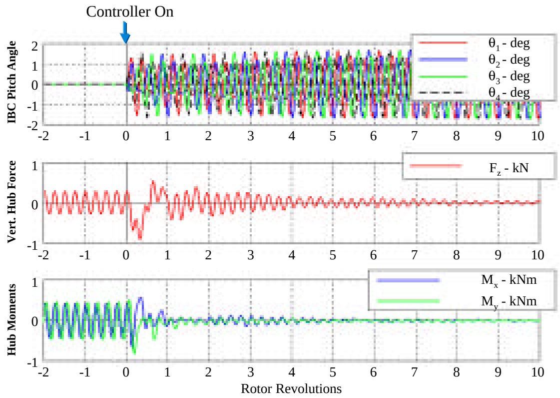

Fig. 11: Simulation of vibration controller activation

The ***realtime code generation*** is performed by using new, 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. The "top level" of the Simulink model with all connections to the "real world" is presented in the appendix.

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 has been performed a second tool from dSPACE, the so called "Control Desk", enables the possibilities of monitoring or changing gain, notch dampings and any other variables presented in Simulink in realtime. The interaction with the realtime controller is realised by using a touch-screen (see Fig. 12). The touch screen is positioned in front of the flight test engineer. The screen gives quick informations about system parameters (e.g. rotor speed), control settings and system alerts. The IBC function state is presented and controlled by push buttons. Coloured lamps present the actual status of the vibration controller and the system itself. For example a green lamp on the left side shows that the actuators are locked and no IBC-input is present (controller idle). This man-machine interface (MMI) has been well received by the flight test engineer and can easily be adapted to other control strategies or different requirements. On the right side a so-called "Data Capture" block can be found. This block allows the storage of all significant data on the Host-PC (Laptop). This data is stored in Matlab readable files and is available directly after the flight test has been finished. This allows a very quick and efficient data processing.

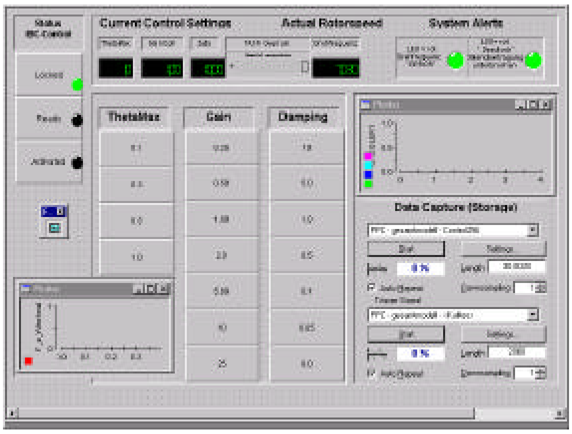

Fig. 12 Touch screen with the Control Desk surface

4 Open Loop Investigations

Special open loop flight measurements on the BO105 S1 are performed immediately prior to the testing of the hub load vibration controller. A list of the test flights with further informations is presented in a separate table of the appendix.

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.

4.1 Hub Load Sensor Check-Up

The testing of the hub load measurement system concentrates on the strain gage signals at the rotating hub arms (flapwise) and at the rotor shaft. A rotor harmonic analysis of the measurements for steady flight condition was performed and used for getting static and blade-number harmonic estimates of the hub loads Fz and Mx, My, respectively. The static (mean) values are well suited to check the sign and the calibrations. The 4/rev values provide valuable information about the vibratory disturbances of the rotor in the fixed system. For example at 60kts/100kts level flight the following 4/rev hub excitation amplitudes were obtained:

	Fz	Mx	My
60 kts	554 N	472 Nm	488 Nm
100 kts	263 N	293 Nm	228 Nm

4.2 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.

Example: Fig. 12 shows for collective pitch control inputs defined by

$$(q_{IBC})_{coll} = 0.44\deg\cdot\cos(4\Omega t - j_{IBC})$$

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

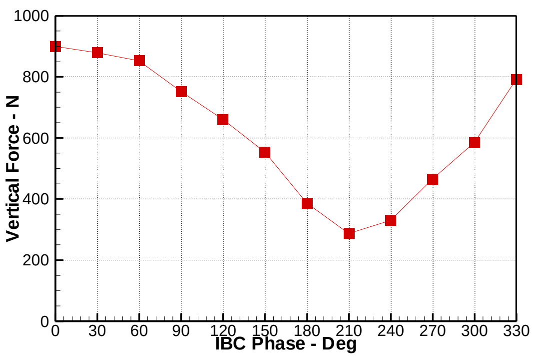

Fig. 12: Vertical hub force in dependence of the IBC phase in level flight (100kts)

Assuming a linear relationship between the inputs and the outputs the transfer functions were defined in section 3.1. 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 (see Ref. 4). For the controller layout the 4/rev transfer matrix elements are of special interest. These elements are collected in the following matrix:

$$G = \begin{bmatrix} 904.3 - 982.0i & 478.2 - 232.6i & 823.4 - 332.4i \\ 338.9 + 469.6i & 178.8 + 893.2i & 695.1 + 403.2i \\ 616.4 - 688.4i & 206.4 + 462.7i & 541.9 - 2088.4i \end{bmatrix}$$

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

For further evaluation the transfer functions are applied for determing IBC-induced 4/rev hub loads. Using the elements of the first row, assuming collective inputs with 0.44 deg 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 13: 4/rev vertical force (Fz)

Fig 14: 4/rev roll moment (Mx)

Fig 15: 4/rev pitch moment (My).

These flight test based hub loads are compared with calculated hub loads (Camrad II). The agreement between calculation and measurement is good. Similar results are obtained for longitudinal and lateral IBC pitch inputs. Summarising the identified transfer matrix can be used with confidence for the setup of the gain matrix of the disturbance rejection controller for the BO105 flight demonstrator.

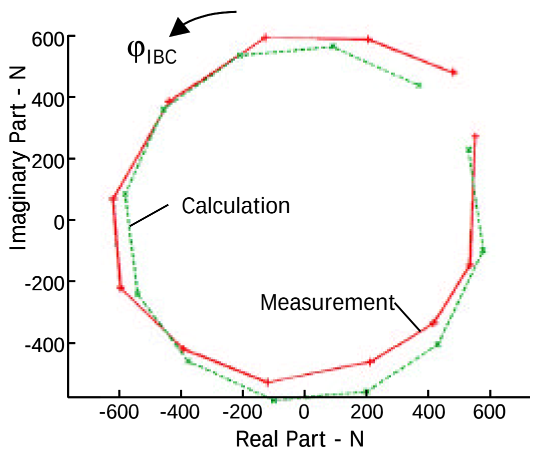

Fig. 13: Comparison of 4/rev vertical forces (Fz) at 100 kts (calculation vs. measurement)

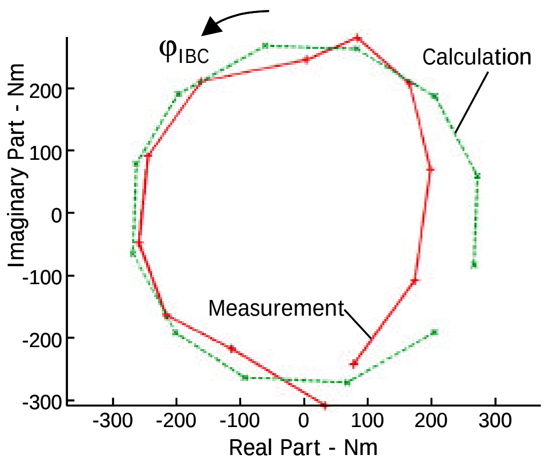

Fig. 14: Comparison of 4/rev roll moments (Mx) at 100 kts (calculation vs. measurement)

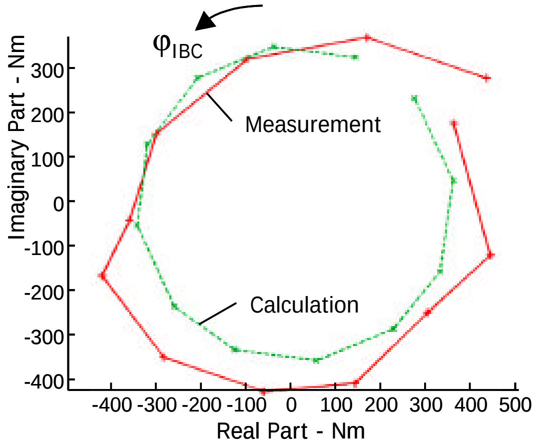

Fig. 15: Comparison of 4/rev pitch moments (My) at 100 kts (calculation vs. measurement)

5 Closed Loop Investigations

The investigations started with the setup of the gain matrix for the hub load vibration controller. As worked out in Ref. 2 the feedback gains are determined by using the 4/rev system transfer matrix elements from section 4.1 with some inflight adjustments for each control channel. A brief overview about the conducted closed loop flights and the obtained results is presented in the table of the appendix. The first flight tests were aimed for testing separately collective IBC pitch actuation with Fz-feedback and cyclic (longitudinal and lateral) IBC pitch actuations with Mx-, My-feedback, respectively. In both cases the flight test results were in agreement with theoretical studies and predictions. These experiments were accompanied with closed loop stability investigations for different gain settings. All results are used for an optimal adjustment of the “decoupled” controller gains defined in Ref. 2. These values are subsequently used as starting gains for flight testing with combined collective and cyclic disturbance rejection control for Fz, Mx and My at 4/rev. The following sections will concentrate on these final closed loop flight tests.

5.1 Controlled Hub Loads and Vibrations

The focal point of the performed flight tests with the complete feedback of the three disturbances was to verify that the suppression of hub loads leads to a reasonable reduction of vibratory airframe vibrations.

For this purpose the BO105 S1 was equipped with additional airframe acceleration pick-ups at the gearbox (top) and at the cabin floor (copilot seat) in x,y,z-directions.

Level Flight: Measurements at forward flight speeds from (60 ÷ 100) kts (IAS) @ 100% rpm and rotor rotational speed variations from (98÷102)% @ 100kts were conducted in order to explore the performance of the hub load vibration controller with notch frequency adaptation. The measured 4/rev hub loads with and without IBC are plotted in Fig. 16 (flight speed variation) and in Fig. 17 (rpm variation). For both parameter variations pronounced reductions of the 4/rev hub load are achieved by the feedback controller with IBC actuation. The following 4/rev hub excitation amplitudes are obtained at 100% rpm by the feedback controller.

	Fz	Mx	My
60 kts	80 N	61 Nm	60 Nm
100 kts	63 N	31 Nm	24 Nm

These controlled vibratory hub loads may now be compared with the uncontrolled case (see section 4.1). A reduction of about 80% is achieved for Fz and of about 90% for Mx, My. The implemented automatic rpm-adaptation of the dynamic compensator (notch) works obviously well, which can be concluded by examination of the controlled load values in Fig. 17: The vibration reduction performance of the controller is nearly independent from changes in rotor speed.

The measured 4/rev gearbox and cabin vibrations are presented in Fig. 18 and in Fig. 19, respectively, for level flight speed variation at 100% rpm. The airframe vibration levels with IBC engaged are reduced in all cases. Remarkable strong reductions are obtained in longitudinal and lateral direction. For example at 60kts level flight the longitudinal gearbox accelerations are reduced from about 0.8g down to less then 0.2g. The cabin vibrations are reduced to values of about 0.05g; an exception is the measured vertical vibration at 100 kts in level flight with values of about 0.08g. In this case the vibration reduction was moderate, which is possibly explained by uncontrolled inplane hub force excitations. Additional informations about the 4/rev cabin vibration amplitudes with IBC actuation are gathered in the table below.

	Vx	Vy	Vz
60 kts	0.04 g	0.02 g	0.06 g
100 kts	0.05 g	0.02 g	0.08 g

Overall the achieved low vibration levels were confirmed by the flight test crew which attests an excellent vibration behaviour of the helicopter with activated controller.

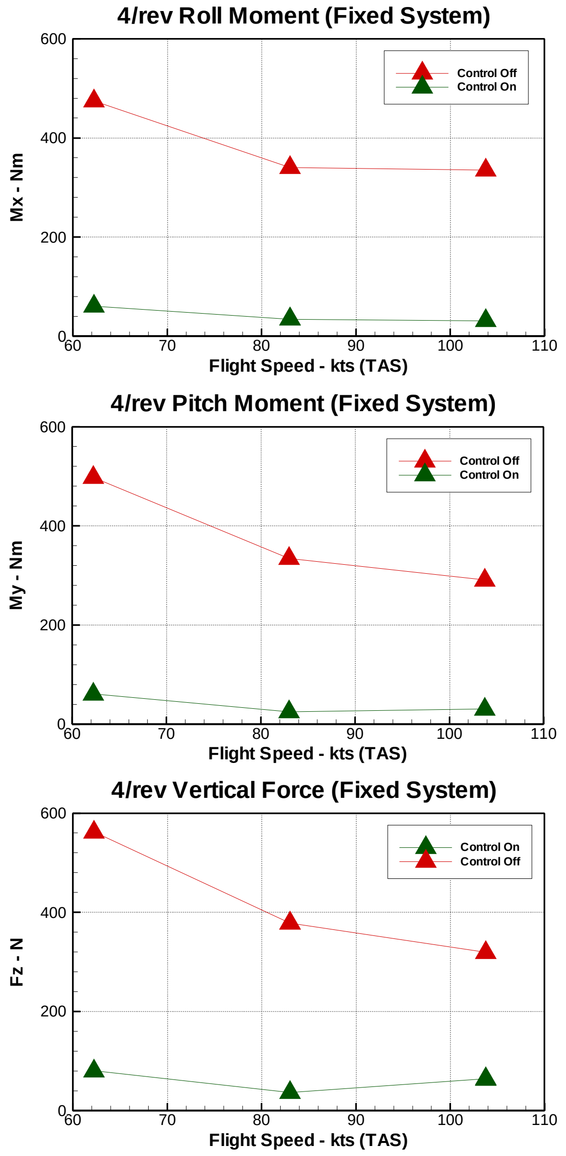

Fig. 16: Controlled hub loads vs. flight speed (100% rotor speed)

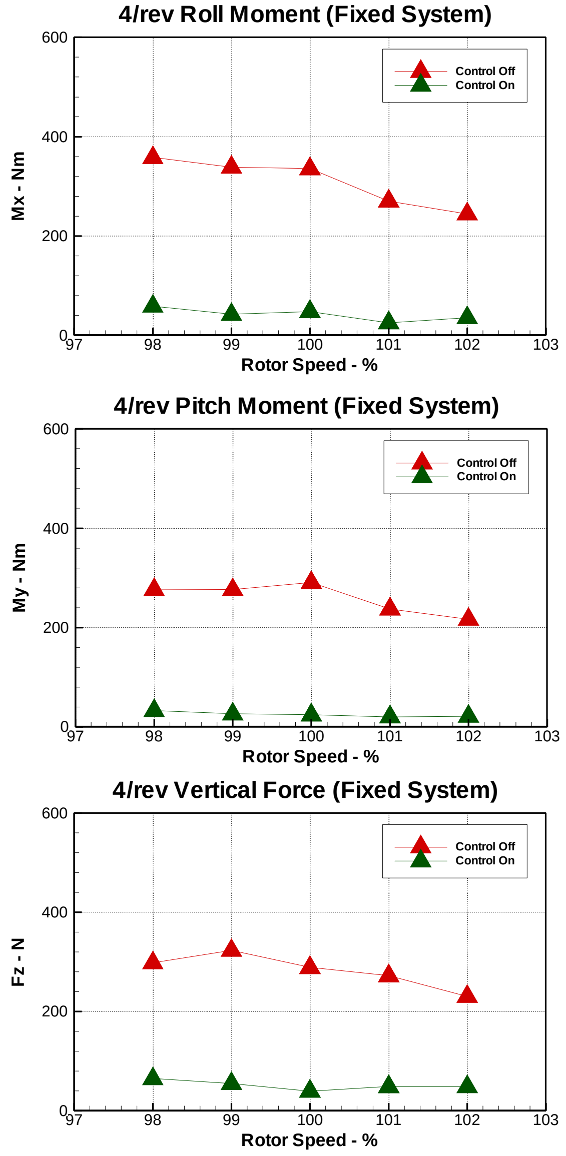

Fig. 17: Controlled hub loads vs. rotor speed (100kts flight speed)

Climb and Descent: The vibration reduction performance of the IBC controller was studied next for climb and descent rates of ±1000 ft/min at flight speeds of 65kts. These tests should provide further insight in the robustness of the installed controller. The measured 4/rev hub excitations and cabin response data is plotted in Fig. 20 and Fig. 21, respectively. Comparing the flight test results with and without IBC, one can conclude for climb and descent flight conditions that the controller efficiently rejects the controlled vibratory hub loads (Mx, My, Fz). This results in a strong reduction of cabin accelerations below 0.05g. Again, the acceleration level in vertical direction is less influenced by the IBC actuations.

Manoeuvre flight: The investigations are concentrated on left and right turns at 80kts with load factors up to 1.2g (30° bank angle). The measured 4/rev hub loads are presented in Fig. 22. Once again the hub load controller shows an excellent performance and reduces all three controlled loads to low values, which are comparable with force (Fz) and moment (Mx, My) data achieved during steady state level flight condition. The corresponding cabin vibrations show the expected low acceleration levels. For example, the 4/rev cabin vibrations for the 1.2g right turn at 80kts are 0.04g in x-direction, 0.02g in y-direction and 0.08g in z-direction with engaged IBC controller. The time domain disturbance rejection controller is well suited for both steady state and unsteady flight manoeuvres. Time constraints have yet prevented flight testing of more advanced manoeuvres for demonstration the whole benefits of the applied control concept.

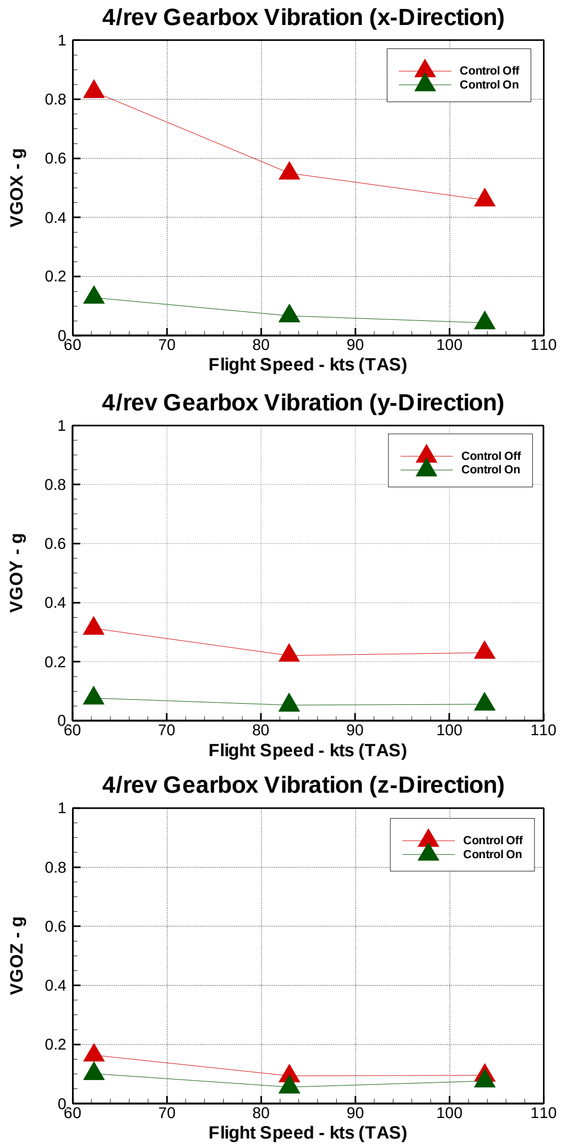

Fig. 18: 4/rev gearbox vibration vs. flight speed (100% rotor speed)

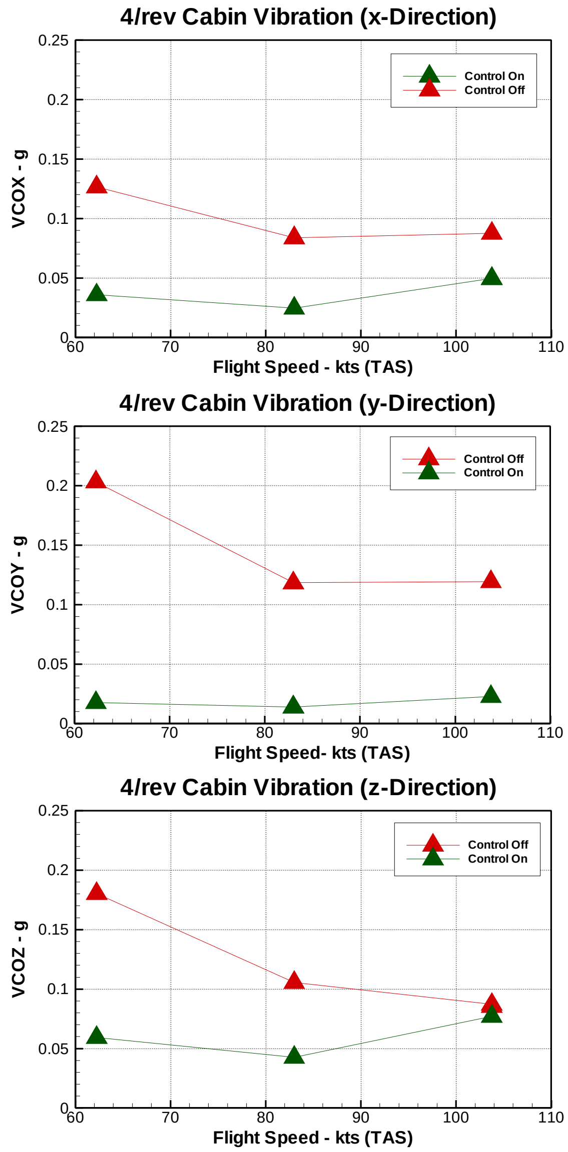

Fig. 19: 4/rev cabin vibration vs. flight speed (100% rotor speed)

5.2 Influence on Uncontrolled Loads

During flight testing of the vibration controller the blade attachment bending moments in flap and in lead-lag directions were recorded, too. Of special interest are here the rotor harmonic lead-lag bending moments which may contribute to fixed system vibration excitations at 4/rev:

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

The flight tested disturbance rejection controller is aimed for cancellation of flap bending induced rotor loads but not of lead-lag bending induced rotor loads, which remain uncontrolled. The hub arm lead-lag bending measurements (see section 3.2) are analysed for 60 kts and 100 kts level flight. The rotor harmonic moment amplitudes in lead-lag direction are collected in the following table.

	M_x - Arm (Nm)		
	3/rev	4/rev	5/rev
60 kts	47 / 54	59 / 63	22 / 27
100 kts	37 / 24	60 / 61	23 / 32

Note: Values are without IBC / with IBC

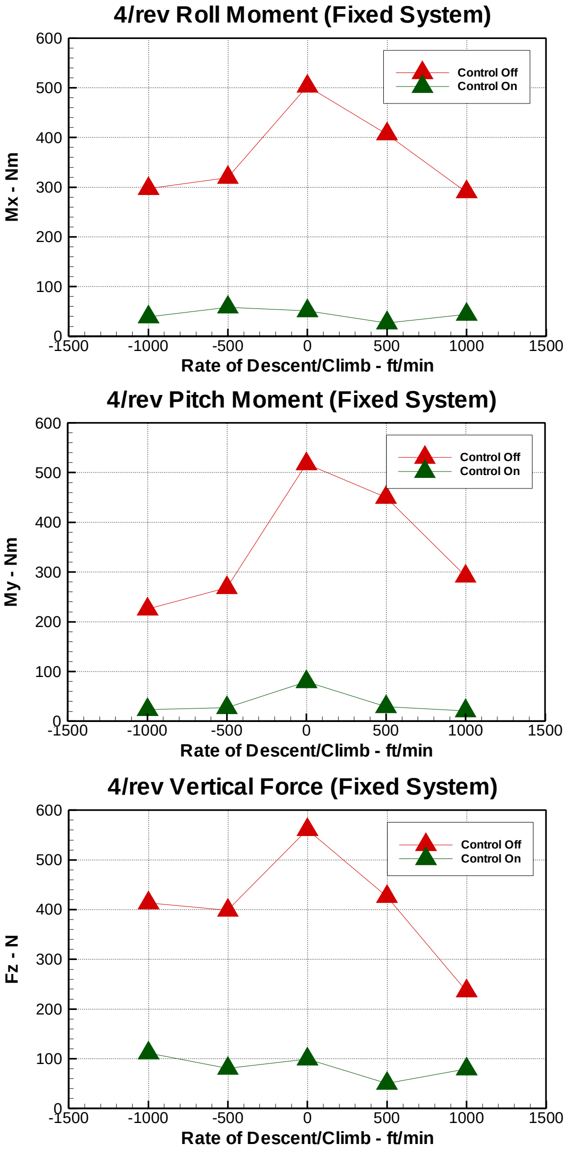

Fig 20: 4/rev hub loads vs. rate of climb/descent at 65 kts

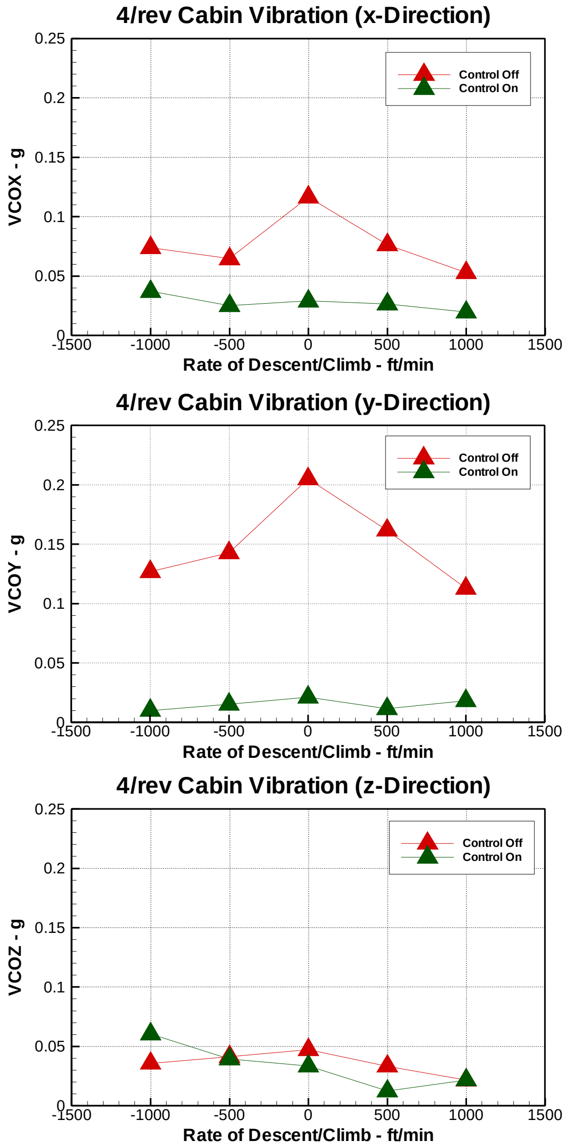

Fig.21:4/rev cabin vibration vs. rate of climb/descent at 65 kts

Obviously, the inplane blade bending loads are hardly affected by the actuation which may be explained by the applied low control gains. For convenience, the amplitude spectra of the lead-lag bending moment at the blade attachment (yellow reference blade) are presented in Fig. 23 without IBC and in Fig. 24 with engaged IBC for the 60 kts level flight case.

5.3 Stability Investigations

Principally, feedback controller are sensitive with respect to stability. Therefore, flight testing of the time domain vibration controller was performed with caution at all development stages. Typically various controller settings were tested by increasing gain values for the three control channels.

Dedicated stability tests with simulated 4/rev reference sinusoidals were superposed on the feedback at the notch inputs. Thus damping margins could be measured from the transients after shutting off the sinusoidal excitation reference. This procedure is presented in Fig. 25 showing the sinusoidal excitation signal (above) and the transient Fz-feedback signal (filtered, below). The transient signal is determined by an exponential decaying signal at about 4/rev, the associated (modal) damping is in the range of (0.3 ÷ 0.6)% for this case. These results confirm the expectation, that the feedback loop is dominated by the notch dynamics for the applied low feedback gains. Theoretical studies have supported this conclusion. Further stability investigations for the vibration controller are required and planned.

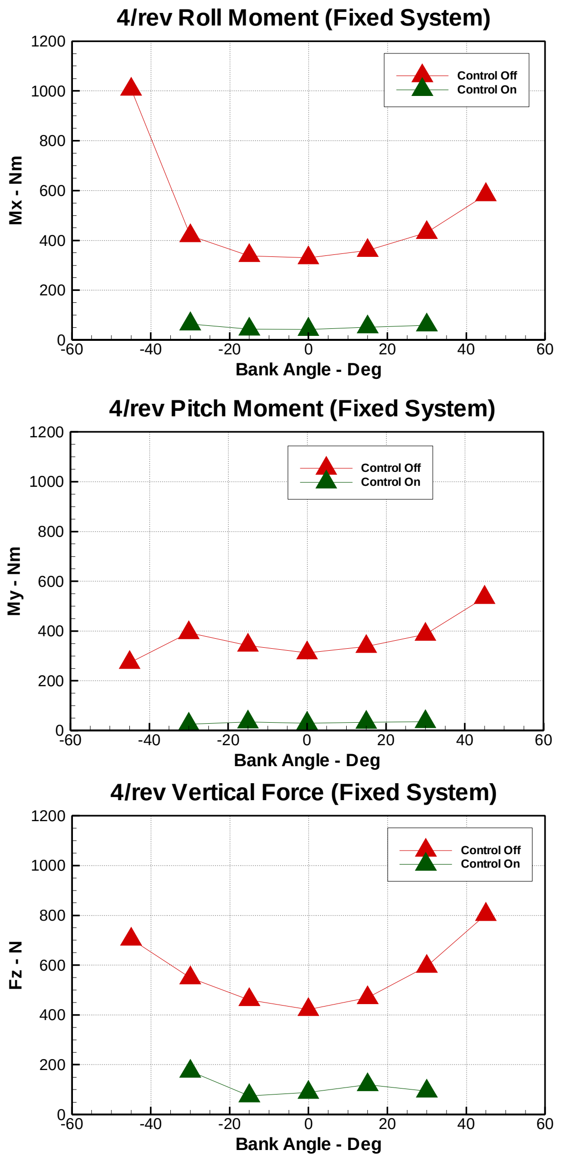

Fig.22: 4/rev hub loads in manoeuvre flights at 80 kts

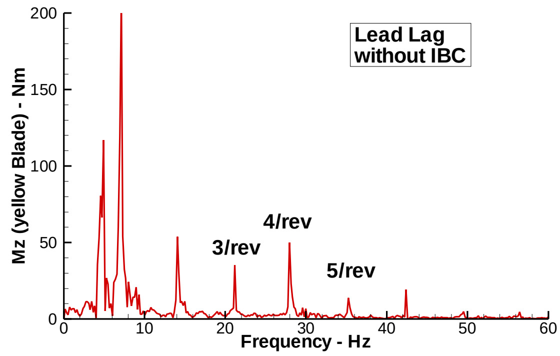

Fig.23: Amplitude spectrum of M_x without IBC

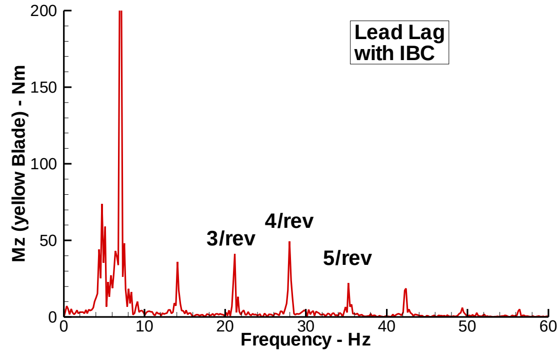

Fig.24: Amplitude spectrum of M_x with IBC

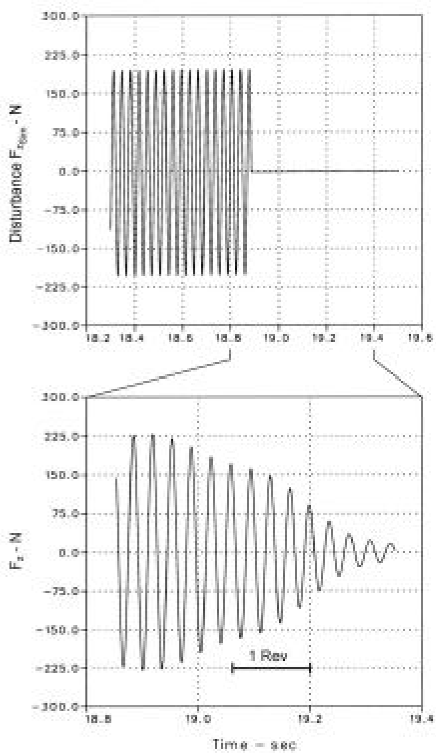

Fig. 25: Evaluation of stability margins from transients (Fz – control)

6 Conclusion and Outlook

Robust disturbance rejection control for airframe vibration reduction was applied on the BO105 IBC demonstrator with remarkable success. The flight tested "fixed-system" hub load controller uses output feedback in the time domain and is aimed for cancellation of blade number harmonics at 4/rev in steady and unsteady flight conditions. The expected rigorous reduction of 4/rev vibrations in the whole aircraft was confirmed by numerous flight tests. As an example the measured cabin vibration spectra of Fig. 26 at 60 kts level flight with engaged IBC are compared with the initial spectra (see Fig. 2) without IBC. The pronounced vibration reduction achievements at 4/rev are obvious. Further flight tests of the controller/sensor system are envisaged, including the control of inplane hub forces and gain scheduling. Last but not least, simultaneous noise and vibration control is prepared for demonstration of the outstanding capabilities of IBC technology.

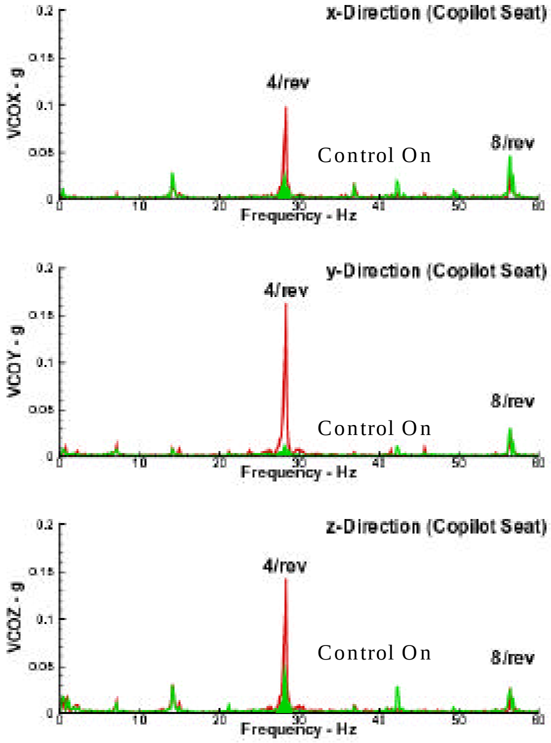

Fig. 26: IBC vibration reduction achievements (BO105 S1 @ 60kts level flight)

Generally the following conclusions can be drawn:

- 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 excitation and airframe response reduction or minimisation; this includes various modern optimal and alternative adaptive control concepts (see Ref. 5-8).
- Realtime vibration controller realisation for the IBC flight demonstrator was highly supported by the power of Mathworks & dSPACE development tool chain.
- 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. Recently, advanced concepts for inflight helicopter identification and model verification have been developed (Ref. 9,10); these methods shall be applied on the IBC flight demonstrator in cooperation with research establishments.

The application of IBC technology on production helicopters is the common goal of various research programs world-wide, see Ref. 11. At ECD the active trailing edge flap concept is pursued (see Ref. 12) and was recently successfully tested on the whirl tower (see Fig. 27). This innovative system will be flight tested on the new BK117 IBC demonstrator (see Fig. 28) this year.

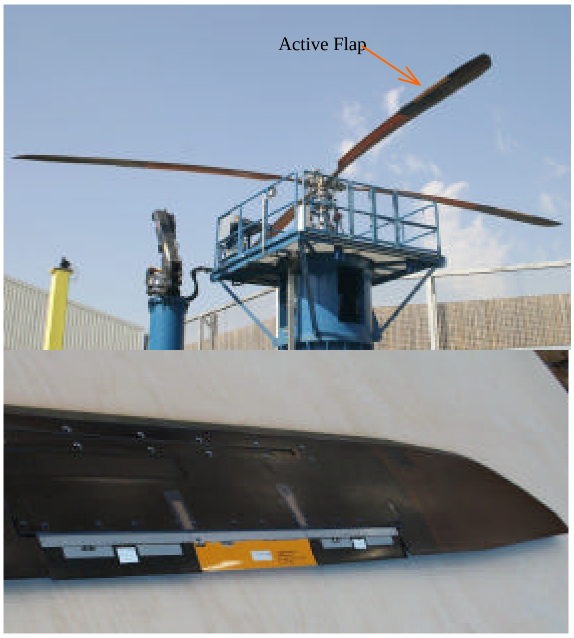

Fig. 27: Experimental main rotor with piezo-active trailing edge flaps on whirl tower

Fig. 28: BK117 S7045 IBC demonstrator

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Appendix

The various open and closed loop flight test activities on the BO105 S1 helicopter with IBC for vibration control are gathered in the table below. On the following page two Matlab/Simulink models of the realised vibration controller (control algorithm and top level view) are shown in some detail.

Performed Open and Closed Loop Flight Tests		
Flight Number	**Aim**	**Results**
F1611	First System Test with IBC Input (3/rev, 4/rev, 5/rev) in Level Flight	Verification of the new applicated Blade Bending Sensors
F1612	Evaluation of System Behavior by IBC Inputs (3/rev, 4/rev, 5/rev) in Level Flight	Transfer Function of the IBC Inputs due to Blade Bending Moments could be evaluated
F1613	System Identification by Collective IBC Input (Calculated in the Fixed System)	Transfer Function of the Collective IBC Inputs due to the Fz Hub Force could be evaluated
F1615	System Identification by Longitudinal and Lateral IBC Input (Calculated in the Fixed System)	Transfer Function of the Longitudinal and Lateral IBC Inputs due to the Hub Moments (Mx, My) could be evaluated
F1618	Closed Loop Testing of the Collective Hub Load Control Path (Fz) in Level and Maneuver Flights	Reduction of the Vertical Hub Force (Fz) up to 85% under all Flight Conditions achievede
F1619	Closed Loop Testing of the Longitudinal and Lateral Hub Load Control Path (Mx, My) in Level Flight with varying Rotorspeed	Reduction of the 4/rev Hub Moments (Mx, My) up to 75%, Remarkable Reduction of the Cabin Vibrations
F1622 F1623	First Stability Investigation of the Vibration Controller (Fz Feedback) with Simulated Disturbance Signal (100N)	First Damping Investigations of the Disturbance Rejection Controller (Fz Only)
F1624 F1625	Closed Loop Vibration Control (Fz) with Rotor Speed and Phase Variation. With and without Simulated Disturbance Signal (100N)	Stability Margins of the Controller could be evaluated
F1628	Stability Investigation Vibration Controller (Fz Feedback) with Simulated Disturbance Signal (200N) and Phase Variation	Evaluation of System Stability and Damping
F1631	Closed Loop Vibration Control with 4/rev Roll (Mx)- Pitch (My)- and Vertical Force (Fz) Feedback in Level Flight	Minimization of the Rotor Loads up to 90% Drastic Reduction of Cabin Vibration in the Range of 60kts up to 100kts with Rotor Speeds of 98% up to 102%
F1638	Closed Loop Vibration Control with 4/rev Roll (Mx)- Pitch (My)- and Vertical Force (Fz) Feedback in Maneuver Flight	Minimization of the Rotor Loads up to 90% Drastic Reduction of Cabin Vibration in Maneuver Flight (Climb, Descent and Turns)

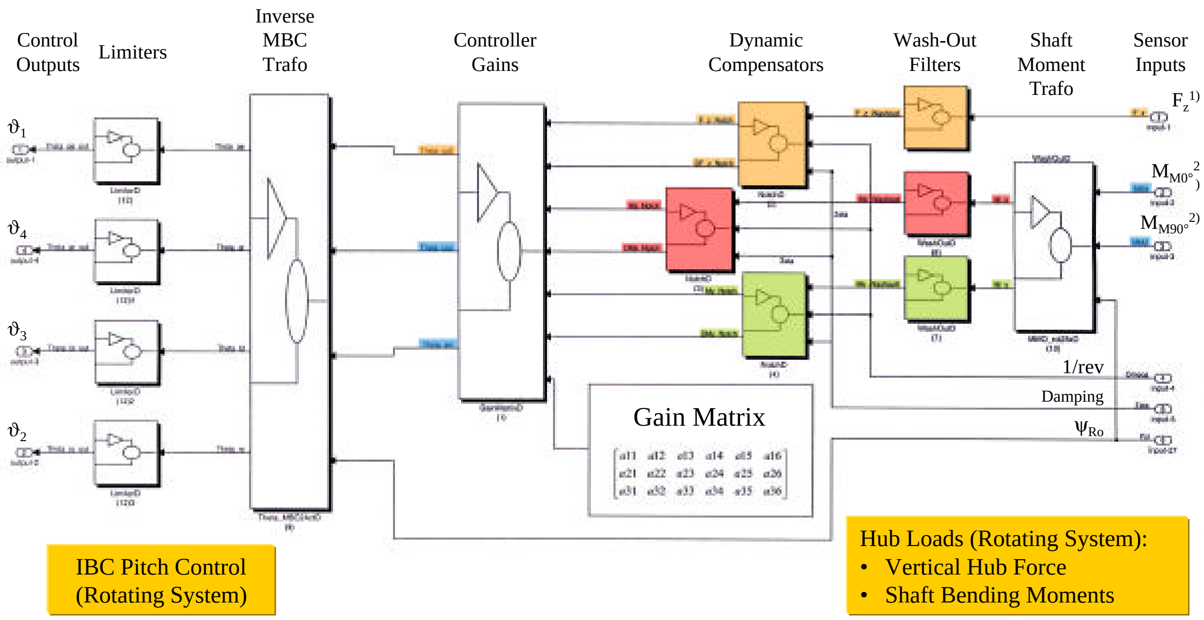

Fig A1: Matlab/Simulink model of the realised vibration control algorithm

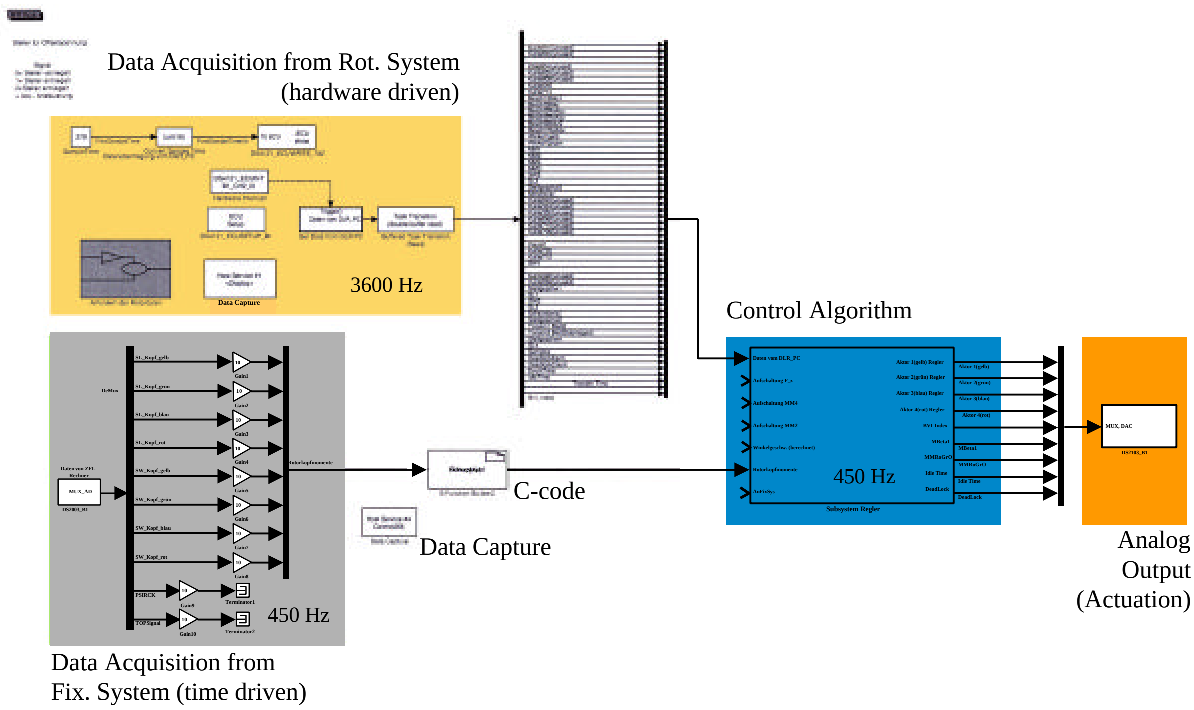

Fig A2: Top level Simulink model of the vibration controller