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INDIVIDUAL BLADE ROOT CONTROL DEMONSTRATION RECENT ACTIVITIES

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Abstract

In the past, the active blade root control system installed on a BO 105 helicopter has been successfully tested in open loop configuration by EUROCOPTER Deutschland GmbH (ECD) and ZF Luftfahrttechnik (ZFL). These flight tests with individual blade root control (IBC) technology have demonstrated the potential of vibration and noise reduction on the BO 105 testbed. Therefore further investigations have been started to evaluate the benefits of closed loop noise and vibration control using IBC technology.

This paper presents recent activities related to the realisation of closed loop control on the BO 105 IBC demonstrator including hardware and software aspects. Special emphasis is given on the required equipment and algorithms for blade vortex interaction (BVI) noise reduction and vibratory hub load suppression.

The noise control concept is based on BVI-index minimisation applying 2/rev IBC feedback. Recent results of flight tests in closed loop BVI noise control configuration are presented and the achieved noise reduction by the usage of microphone signals is demonstrated.

The vibratory 4/rev hub load control is based on a dynamic feedback controller for disturbance rejection. This concept is discussed and a short outlook on the planned flight tests for validation is given, too.

The presented concepts are applicable for advanced individual blade actuation systems including the envisaged piezo-active trailing edge flap currently developed under the sponsorship of the German ministry for research and technology (BMFT)

1 Introduction

The BO 105 S1 flight demonstrator (see Fig. 1) uses proven servo-hydraulic blade pitch actuators with adequate authority for significant noise and vibration reduction, see Ref. 1. This actuation system is controlled by an embedded digital computer in combination with high performance signal processing equipment for the data transfer between the rotating and non-rotating system. In order to reduce the effort for the development of realtime controller software an efficient security concept is realised in accordance with civil airworthiness requirements. Moreover, special interfaces are provided for the communication between the flight test engineer and the real-time computer system. For vibratory hub load and exterior noise control a complex sensor system is installed consisting of multi-blade and mast bending strain gauges, blade pressure pick-ups, landing gear mounted microphones and various accelerometers.

Fig. 1: BO 105 S1 IBC demonstrator in flight

Tab. 1: Recent and planed activities using individual blade control (IBC) on the BO 105 rotor system

Year	IBC Tests	Actuator Authority	Flight Speed (Wind Speed)	IBC Amplitudes	IBC Harmonics	Objectives
1990	***First flight tests*** Open loop single-harmonic input	0.25°	60/115 kts,	0.16°	3/rev, 4/rev, 5/rev	Functionality tests
1991	***Flight tests with increased authority*** Open loop single-harmonic input	0.49°	60/110 kts, 65 kts descent	0.40°	3/rev, 4/rev, 5/rev	Vibration and BVI noise characteristics
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 2/rev noise control	1.1°	65 kts descent	1.0°	2/rev	BVI noise reduction
Next	***Flight tests with vibration controller*** Closed Loop Time domain (TD) control	1.1°	65 ÷ 110 kts	max. 1.0°	3/rev, 4/rev, 5/rev	Vibration reduction

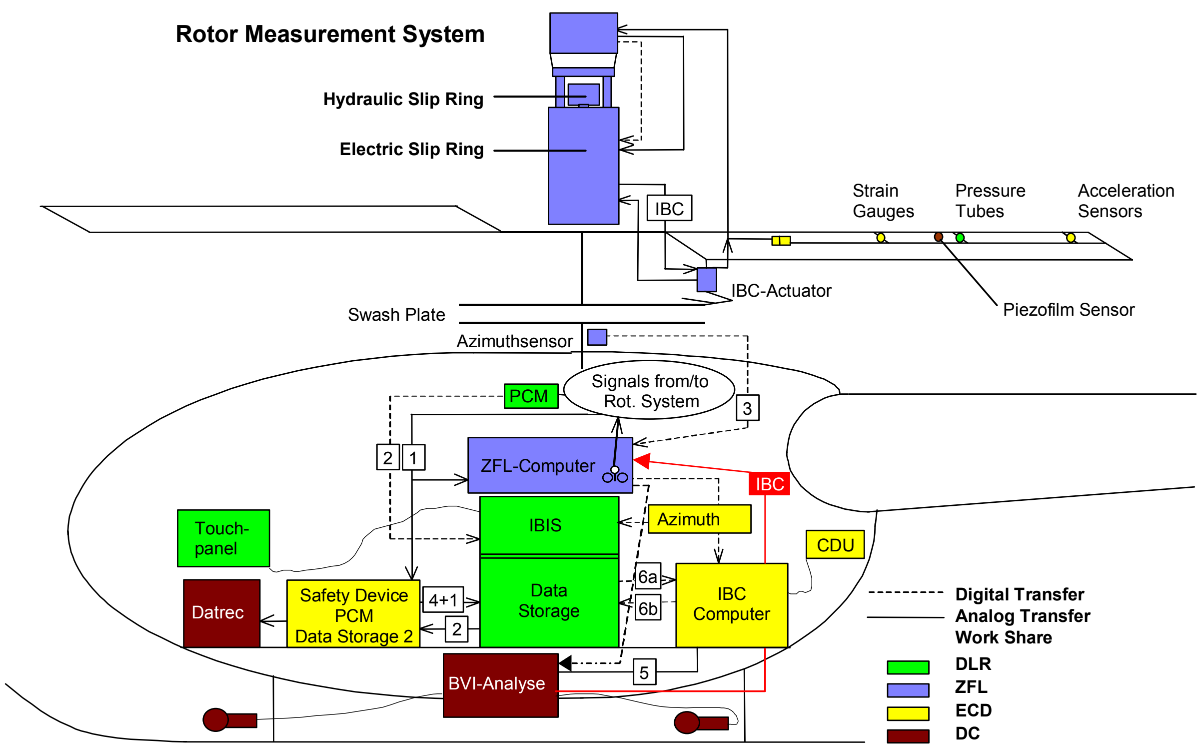


Fig. 2: System architecture of the closed loop IBC system

The BVI noise control is based on a newly developed concept for minimising an appropriate BVI-index using either blade pressure or microphone signals. The applied feedback concepts use the noise reduction capabilities of 2/rev IBC feedback control for BVI relevant descent flights. An inflight validation of this concept is presented in some detail. The vibratory 4/rev hub load control is based on an output feedback controller for disturbance rejection in the time domain. The special features and advantages of this concept are discussed with emphasis on cruise flight conditions. In addition, the efficiency of the controller concepts are demonstrated by extensive theoretical simulations using sophisticated mathematical models and software tools.
An overview over various experimental investigations with the BO 105 IBC system are gathered in Tab. 1 including most recent flight tests and planned activities in the near future.

2 The IBC Flight Test Equipment

In order to prepare the 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 are:

- Integration of an embedded control computer for noise and/or vibration control
- Integration of a fast real-time computer for BVI detection
- Modification of the IBC actuator control computer system by ZFL for high response feedback applications
- Adaption of the safety concept for closed loop controller testing
- Integration of modern piezofilm sensors for BVI detection.

The final system architecture of the demonstrator for the envisaged closed loop activities is shown in Fig. 2 presenting the workshare of the individual companies. The integration of the IBC computer and the data acquisition system (IBIS) into the fuselage is shown in Fig. 3. This computer is based on a multiprocessor structure without internal bus developed by DLR (Ref. 2). The chosen transputer based approach leads to a modular and easy expandable design of the data acquisition system, which eases the interfacing to other devices like the control computer and the rotor measurement equipment. This system 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 (Ref. 3)

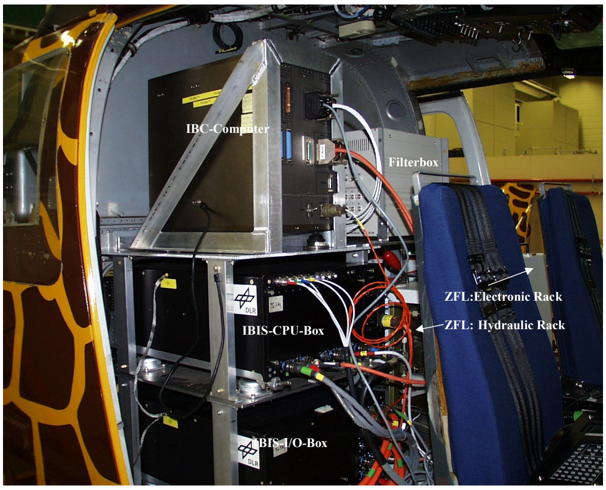


Fig. 3: Integration of IBC computers into the helicopter

2.1 IBC Actuation System

The hydraulic IBC actuating system which is integrated in the BO 105 and developed by ZFL has been already applied during the flight tests in spring 1998 (Ref. 1). This experimental system can be divided into two parts:

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

The hydraulic power will be 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 through an electrical slip ring. Although the system is an experimental arrangement in modular design, it has proven high mission reliability throughout all flight test campaigns.

2.2 IBC Actuator Units

A central element of the blade root control system are the hydraulically powered actuators. The actuators replace the conventional push rods between the pitch link horn and the swashplate and thus become part of the primary flight control system, see Fig. 4. The working piston stroke can be controlled for each actuator separately within the range of +/- 1.1° blade pitch angle. In order to further improve the bandwidth of the four hydraulic IBC actuators, each actuator is equipped with a local position feedback loop designed in the time domain ("inner loop"). The actual piston position is measured by a position transducer (LVDT) inside each actuator. In addition each actuator is equipped with a piston velocity transducer (LVT) and an axial force sensor for monitoring and safety purposes. The essential actuator data are listed in Tab. 2. Regarding the frequency range of interest, the harmonic response behaviour (phase delay) of the actuators is plotted vs. the rotor harmonics in Fig. 5.

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

Fig. 4: Servo-hydraulic actuator

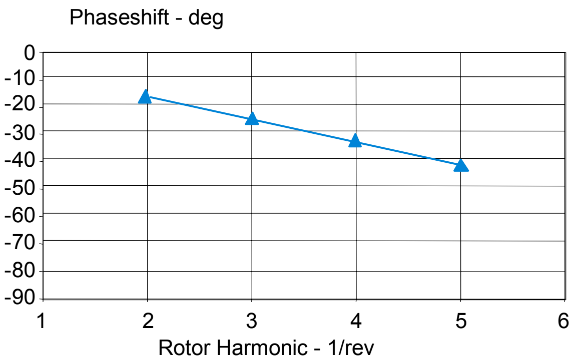


Fig. 5: Measured phaseshift between actuator access and actuator displacement

2.3 Safety Design Aspects

For flight testing of the IBC an appropriate safety concept has been developed and tested. A core item of this concept consists in the ability to switch off the control signal and to activate the locking sequence in case of IBC control malfunction. This feature is ensured at any time under all conditions. The locking sequence will be released by a very fast pressure drop of the hydraulic system, triggered by various sensor signals shown in Fig. 6. The locking actuation power required for pushing the working piston into the mechanical locking position will be provided by a double helical spring. This spring unit will relax in case of depressurising the hydraulic system by switching several solenoid valves. The system is constructed in such a way that every loss of hydraulic pressure, in case of leakage or voltage drop on the solenoids (triggered or unintended) will release the locking sequence.

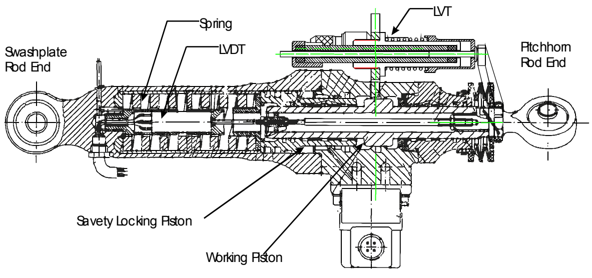


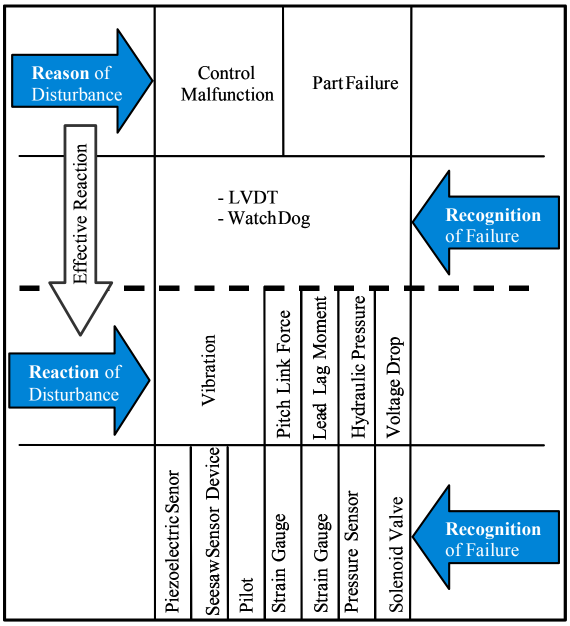
Fig. 6: Safety devices and sensors of IBC actuator

The depressurisation as well as the additional locking sequence are realised as safe-life design by duplication of single solenoid valves and helical locking springs. The mechanical elements of the actuator have been designed to take into account the safe-life principle and are classified for the purposes of the JAR29.601 as "critical parts". The compliance with fatigue demands have been shown by intensive bench testing. The identification of malfunctions that lead to warnings or shut-offs is listed in Tab. 3. In this table the distinction is made between the

- physical cause and
- resulting effects

of disturbances and their recognition. The architecture of the safety system secures that any disturbance is detected and starts an automatic emergency-shut-off. This concept reduces the effort for inflight software development. The safety design and shut off philosophy is presented in Fig. 7.

Tab. 3: Safety concept matrix



This figure shows how a number of physical parameters, converted to electrical signals, trigger the shut-off solenoids for releasing the locking sequence. In addition a manually operated shut-off valve is installed. This safety concept has proven its reliability in flight in the past as well as in the present campaign.

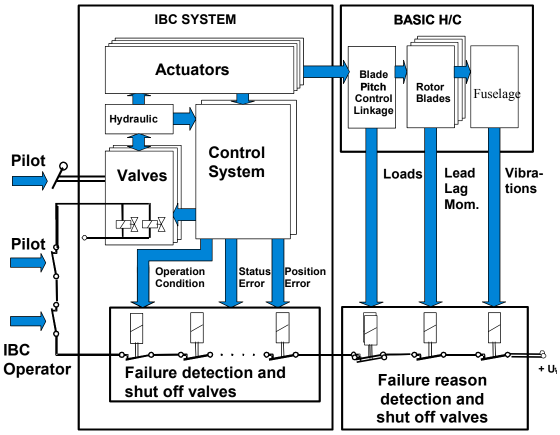


Fig. 7: Principle layout of IBC safety system

3 IBC for Environment and Comfort Improvement

The application of IBC offers a large potential for improved rotor characteristics by modified lift distribution over the rotor disk. Therefore, higher harmonic control can be used for pure aerodynamic applications e.g. rotor performance improvements and stall delay at high speed. Nevertheless, the most promising areas for a broad commercial introduction of IBC systems are seen in the fields of environment protection by external noise reduction and comfort improvement by reduced vibration levels. Both phenomena are caused by aerodynamic excitations of the main rotor blades. Typical inflight blade pressure measurements at the blade tip (BO 105 S1) are plotted in Fig. 8 for two selected flight cases:

- Descent flight at 65 kts with pronounced pressure spikes by BVI producing the annoying blade slap
- Horizontal flight at 110 kts with typical higher harmonic pressure components (e.g. 3/rev, 4/rev, 5/rev) resulting in vibratory hub loads

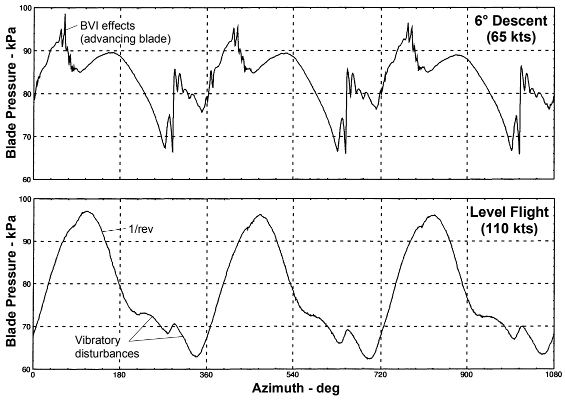


Fig. 8: Typical inflight blade pressure measurements, sensor position at 97% radius and 3% chord (BO 105 S1)

The development of technologies offering a significant reduction of external noise is driven by noise regulations demanding for quieter helicopters in order to avoid flight restrictions in the vicinity of highly populated cities or other noise sensitive areas (e.g. EMS services/medical transports to hospitals). In contrast to the noise topic, the envisaged reduction of vibration levels aims directly on improved customer acceptance minimising the existing comfort gap between fixed wing aircrafts and rotorcrafts. Furthermore, vibration reduction in general is very attractive to helicopter operators in terms of reduced maintenance costs by improved fatigue behaviour of critical components.

Results of the NASA Ames wind tunnel tests have demonstrated that obviously no coherent dependency exists for the control strategies of optimal BVI noise control and optimal vibration reduction (Ref. 4). Therefore, advanced control concepts for simultaneous control of noise and vibration need the potential to manage contrary control targets. Installed on a four or more bladed rotor, IBC is an ideal candidate for this control by using the additional degrees of freedom due to independent blade actuation compared to pure swashplate control. Simultaneous noise and vibration reduction may be achieved by separation of blade control by rotor modes and/or actuation frequencies.

The exploration of the NASA Ames wind tunnel test campaigns has shown that 2/rev input in the rotating system is very efficient for BVI noise control of the BO 105 rotor system. In accordance with other HHC activities by swashplate actuations (Ref. 5) and theoretical investigations, the combination of 3/rev, 4/rev and 5/rev input in the rotating system for a four bladed rotor has proven to be very effective for the reduction of blade passage frequency vibrations in the fuselage. Vibrations at the first blade passage frequency typically show the highest level in the frequency spectrum.

The experimental and theoretical results have lead to a modular controller architecture consisting of two separate tasks, the BVI noise control task and the vibration control task. Fig. 9 demonstrates the decomposition of the simultaneous controller into two feedback loops which are connected in parallel. Regarding the vibration controller, a formulation of the feedback loop in the fixed system offers major advantages for the design of a dynamic disturbance rejection controller. Feedback sensor signals which are acquired in the rotating system are digitally processed for provision of transformed feedback signals in the fixed frame. The vibration controller output variables correspond to 4/rev collective, lateral and longitudinal actuation modes in the fixed system. These control signals are subsequently transformed back into the rotating system for generating the required blade root pitch inputs, i. e. 3/rev, 4/rev and 5/rev signals.
Therefore, the controller decomposition is achieved in a very natural manner by assigning collective, lateral and longitudinal blade pitch actuation modes to the vibration reduction controller – corresponding to higher harmonic swashplate actuation – and by assigning the remaining differential actuation mode to the BVI noise controller. In contrast to the noise controller with prescribed actuation frequency of 2/rev, the actuation of the collective, lateral and longitudinal modes is not restricted to 4/rev as the applied time domain controller which features dynamic (servo) compensators is able to react to transient response.

Furthermore, this approach offers the possibility to develop, to test and to validate the two control tasks for BVI noise and vibration reduction separately in a first stage. If the applicability and the efficiency of the noise and vibration controllers have been verified by flight tests, the IBC controller will be synthesised as second step by embedding both tasks into an overall framework. This paper puts the focus on the first development phase dealing with separated BVI noise and vibration control.

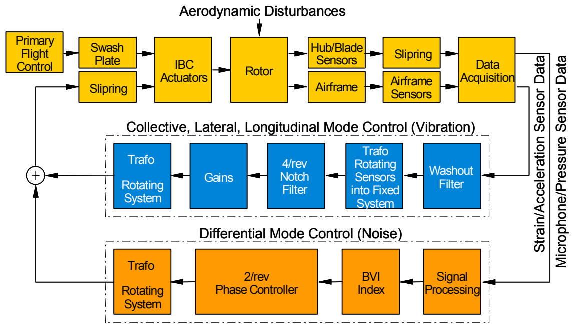


Fig. 9: Controller architecture for simultaneous BVI noise and vibration control

4 BVI Noise Control

A specific annoying noise is radiated by a helicopter if the blade tip vortex collides with a following blade. The so-called Blade-Vortex-Interaction (BVI) noise is primarily radiated during landing approach, when the helicopter is descending into its own rotor wake. Depending on the helicopter design and the actual weight, BVI noise may be generated over a large region of descent flight conditions.

4.1 BVI Detection

There are two possible ways to detect the BVI noise. The first method is based on blade integrated sensors in order to measure the pressure distribution on the rotor blade (e.g. Kulite or piezoelectric sensors). The second method consists in outboard microphones which are directly sensing the acoustic field radiated by the main rotor. For both approaches an BVI-index, correlated to the BVI noise emission has to be derived by an appropriate analysis of the sensor signals. In the following sections a brief review of the different sensor types and the working principle of the BVI detection is given.

Kulite Pressure Transducer

Kulite transducer sense the local blade pressure distribution which changes rapidly when a vortex interacts with a rotor blade. Experimental data generated with blade pressure transducers have lead to the conclusion that every blade-vortex-interaction causes a negative and positive peak combination. This pressure jump is more pronounced the closer the transducer is located in the vicinity of the leading edge where the airfoil’s suction peak can be expected. Based on this information a set of different algorithms for BVI noise estimation was developed. The first algorithm is focused on the blade pressure distribution. The low frequency part of the transducer signals are generally eliminated first by using a high-pass filter. The resulting signals closely represent the BVI-relevant pressure disturbances. Typical blade leading edge pressure data at the tip

(0.97R) are presented in Fig. 10 for the 6° descent flight condition at 65 kts for one rotor revolution:

- Reference case (no IBC input)
- IBC cases with 2/rev blade pitch angle of 1° amplitude and both 60° and 240° phase shift.

The 2/rev blade pitch control inputs are defined for blade 1 by:

$$\theta_{IBC} = A_{IBC} \cos(2\Omega t - \phi_{IBC})$$

with $\Omega = 7.07$ Hz nominal rotor speed

Obviously the applied 2/rev IBC inputs affect the strength of the blade-vortex-interactions. At the advancing blade the BVI pressure spikes are strongly reduced for the 60° phase pitch control input.

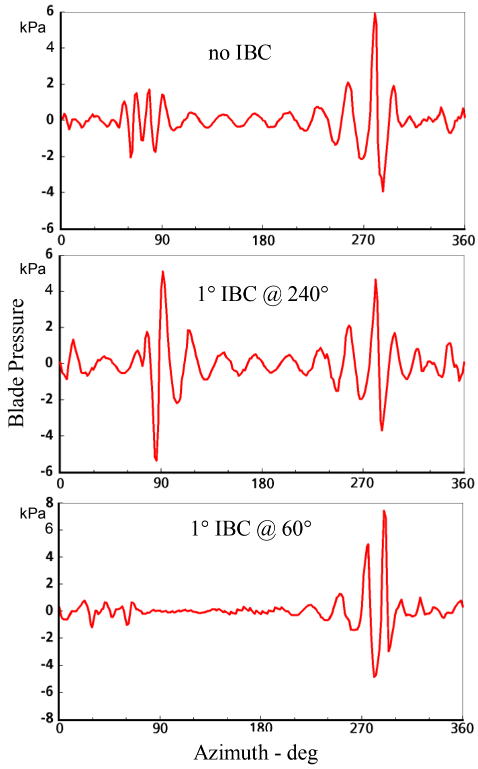


Fig. 10: Typical blade leading edge pressure data, sensor position at 97% radius and 3% chord (BO 105 S1 at 6° descent with 65kts)

On the base of these BVI relevant blade pressure signals an appropriate BVI-index may be evaluated by using fast fourier or wavelet transformation techniques. The results achieved with wavelet transformation are shown in Fig. 11. The good correlation between the BVI noise level measured on ground and the BVI-index is obvious, especially for the range of IBC phase inputs below 180°. A further refinement of these techniques is possible by pre-weightening the BVI-induced pressure data in order to account for blade vortex interaction length representing another prime parameter for the BVI noise intensity. The resulting BVI-index is plotted in Fig. 11, too. Obviously this approach leads to a substantial improvement also for IBC phase angles above 180°. An alternative direct method for defining an BVI-index is based on substituting the blade pressure by the corresponding pressure gradients. Related concepts are described in Ref. 6,7.

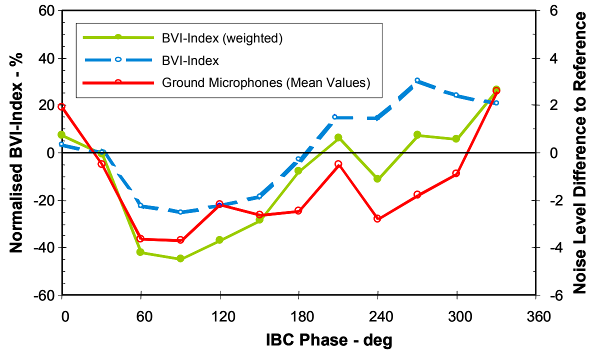


Fig. 11: Comparison of BVI noise level on ground with BVI-index results derived by wavelet transformation

Acoustic Outboard Detection System

An acoustic detection system based on outboard microphones was successfully tested during the past open loop test campaign. This system has been adopted for the recent flight tests in the closed loop configuration. The main aspect for this choice consists in the fact that the microphones are part of the non-rotating system and are directly monitoring the acoustic field. The signal processing and the BVI analysis are less complex than for blade-integrated sensors an therefore easier to realise for first flight tests. The difficulty of outboard microphones is their dependency on the directional characteristic of the BVI sound sources. For this reason mounting locations have to be found which ensure BVI detection at different flight conditions. Within this program six microphones have been mounted at the helicopter skids as shown in Fig. 12.

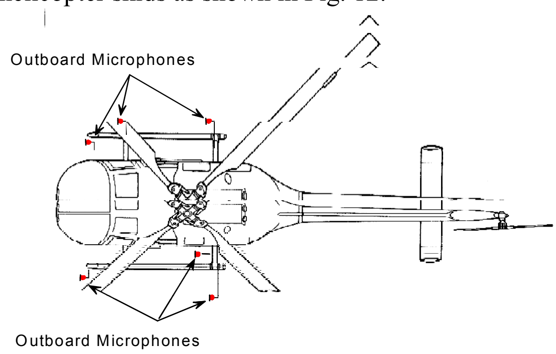


Fig. 12: Schematic view of helicopter with outboard microphones

At the landing gear, three microphones are installed on the advancing blade side and three on the retreating side. For the closed loop tests only the microphones at the advancing blade side were used.

In a first measurement campaign the skid mounted microphone signals were compared with the signals of three ground microphones, located at the advancing, center and retreating side of the rotor. Special interest was directed towards the sound pressure level differences between reference and IBC flights with 1° IBC inputs at 2/rev and different phases. The most essential results are presented in Fig. 13 where mean sound pressure level (SPL) differences of skid and ground microphones to reference flights are plotted against the IBC phase. As indicated, the two sets of microphones measure a very similar behaviour. Both sets identify a maximum SPL reduction at approximately 60° IBC phase in accordance with the results derived from blade pressure measurements.

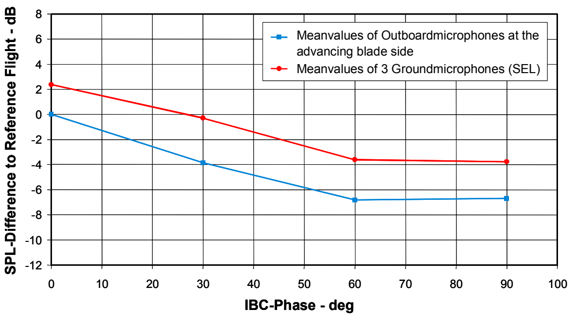


Fig. 13: SPL-Differences of skid mounted and ground microphones at 1° IBC input and different phases (65kts @ 6° descent)

The absolute values differ by 2-3 dB, with a higher reduction at the outboard microphones. Reasons therefore might be some near field mounting effects of the skid microphones as well as influences of directional characteristics of the BVI noise. Nevertheless the similar SPL characteristic of the two curves confirms the usage of skid mounted microphones as a BVI indicator.
Due to this encouraging results a control variable based on outboard microphones has been established for closed loop tests. The main differences of the noise signal characteristic between BVI and non BVI flights are found in their harmonic contents. As BVI noise is very impulsive its frequency spectrum contains many higher harmonic components, as can be seen in Fig. 14. As far as BVI appears a new set of higher harmonics occurs which leads to the very annoying BVI signature. These typical harmonics almost disappear without BVI, as shown in the frequency spectrum of Fig. 15.

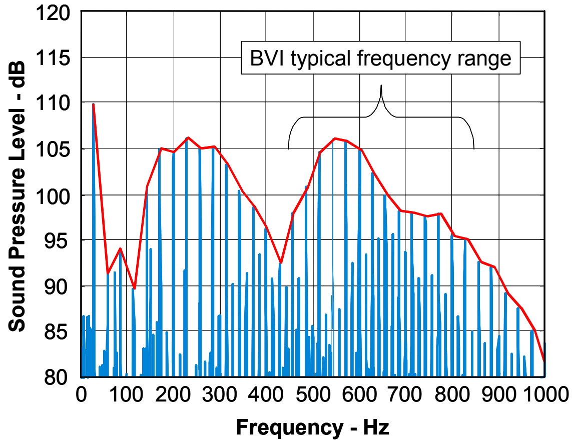


Fig. 14: Typical BVI sound pressure spectrum at the skid microphones

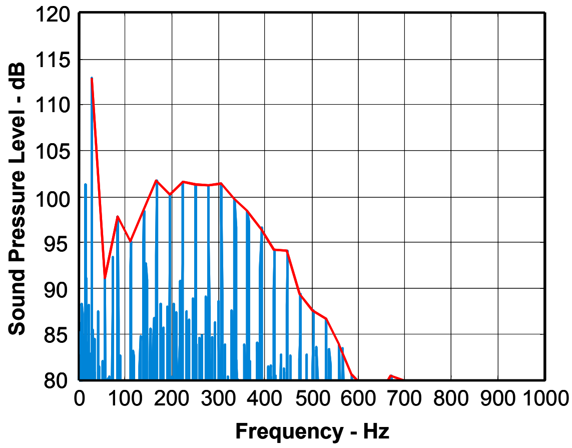


Fig. 15: Typical sound pressure spectrum at the skid microphones with minimum BVI (1° amplitude @ 60° IBC phase)

Both spectra were measured during a 6° descent flight of the BO 105 test helicopter, the first without and the second with an open loop IBC input for minimum BVI. Similar results have been obtained at several descent flight angles.

Due to the differences of the harmonic components between BVI and non BVI flights it seems logical to define some kind of pressure spectrum distortion factor as control variable. This so called BVI-index is defined as the quadratic pressure level of the typical BVI frequency range normalised by the total level measured with the skid microphones. As an example, Fig. 16 shows the results for the 8° descent flight. During the reference flight condition a high index value is calculated indicating strong BVI. When IBC is activated during the descent flight the index reduces remarkable. After IBC is shut down and in case of still existing reference conditions the index rises again.

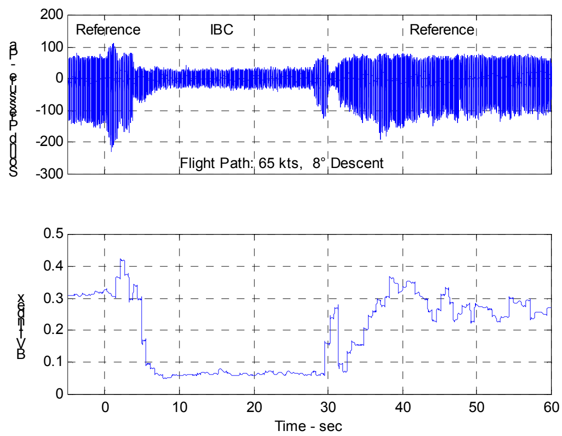


Fig. 16: Sound pressure and BVI-index for a 8° descent flight at 65 kts (without / with IBC)

All flights done so far - with different descent angles or level flights with different speeds - showed a similar behaviour. Therefore this outboard microphone based BVI-index is used as control variable for the acoustic closed loop controller.

Advanced Acoustic Piezofilm Detection System

Piezofilms are a new sensor type for BVI detection which, if placed on a "hard" structure like a rotor blade, have the capability to sense body sound very well. Due to this property, piezofilms are able to detect a vortex which hits the blade surface and thus can be used for BVI detection. A schematic solution for the integration of such a sensor into the rotor blade is presented on the left side of Fig. 17. In this case four independent sensors (S1-S4) have been placed on a carrier plate, in order to achieve a fail-safe system. The final integration of this sensors is shown on the right side.

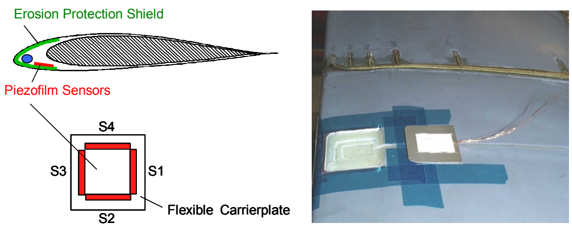


Fig. 17: Integration of the piezofilm sensor

The performance of the piezofilm sensors for BVI detection was investigated in several flight tests. The sensor behaviour with respect to different descent flight conditions is shown in Fig. 18. This figure presents the high-pass filtered data normalised by the overall RMS value. The piezo signals depend on the flight path angle of the 65 kts descent flights and show a strong increase at 6° to 8° where maximum BVI noise is expected.

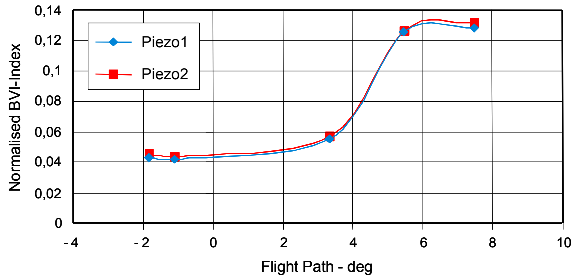


Fig. 18: Signature behaviour of piezofilm sensors at descent flights with 65 kts

The application of this new and robust piezo electric sensor concept for BVI noise control is planned for the very near future.

4.2 Control Concept

The inflight verification of 2/rev IBC for BVI noise reduction has been started recently by testing the microphone based concept (Ref. 8). An overview of the developed control system for the BO 105 S1 demonstrator is shown in the scheme of Fig. 19. Some details of this closed loop control are presented in Fig. 20 using microphone signals for the realtime evaluation and minimisation of the mentioned BVI-index based on sound pressure signals. A “Golden Section” algorithm is applied for optimising the 2/rev IBC phase angle towards the minimum of the BVI-index. The Golden Section rule (see Ref. 9 for more details) is a quite simple and effective procedure for the onedimensional minimisation of an arbitrary nonlinear function. The IBC amplitude was not optimised during the first tests and was therefore kept at a constant value of 1°. This approach was in accordance with open loop flight tests (Ref. 1, 10) which generally have indicated that the IBC amplitude of 1° is most favourable for the reduction of the BVI noise emission.

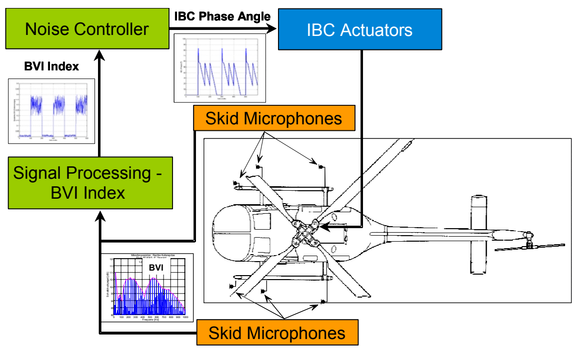


Fig. 19: Schematic view of the noise control arrangement

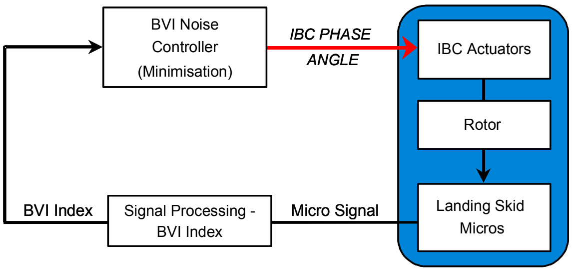


Fig. 20: BVI noise control concept

4.3 Flight Test Results

The focal point of the performed flight tests with the BO 105 S1 was to verify that the skid mounted microphones and the related BVI-index are suitable for noise feedback and that the established control algorithms for the BVI reduction work properly under real environmental conditions. Two different 2/rev control laws were implemented on the control computer:

- A one-parameter control law with *constant* IBC amplitude of 1° corresponding to about 3.2 mm actuator stroke and *variable* IBC phase
- A two-parameter control law with both *variable* IBC amplitude and phase.

The first closed loop flight tests with the one-parameter control algorithms have been performed with a flight speed of 65 kts and a slope angle of 6°, which are typical flight conditions for maximum BVI on the BO 105 (Ref. 1) and which correspond to a descent rate of 600 ft/min.

In Fig. 21 the IBC actuator displacement, the computed BVI-index, the processed IBC phase and the flight path are plotted vs. time. The first seconds of the plot are related to the transition of the helicopter from horizontal flight to descent flight. If the descent conditions (600 ft/min) are almost reached the BVI-index is increasing dramatically. The reaction of the control computer on this increasing BVI-index is identified clearly in this figure. After approximately 5 sec the BVI-index is highly reduced by the noise control computer. About 4 sec later the expected "optimum" phase is found converging to a value of about 52°. As the rate of the IBC input is limited artificially for testing purposes of the noise controller, this slow transient behaviour will be easily improved in the future by relaxing the limitations. At test time 37 sec the BVI-index is slowly increasing due to flight path changes and/or environmental reasons causing the control computer to restart the phase optimisation and to find a new optimum at 45° IBC phase. After switching off the noise control, the BVI-index is rising up again to the value at the beginning of this sequence.

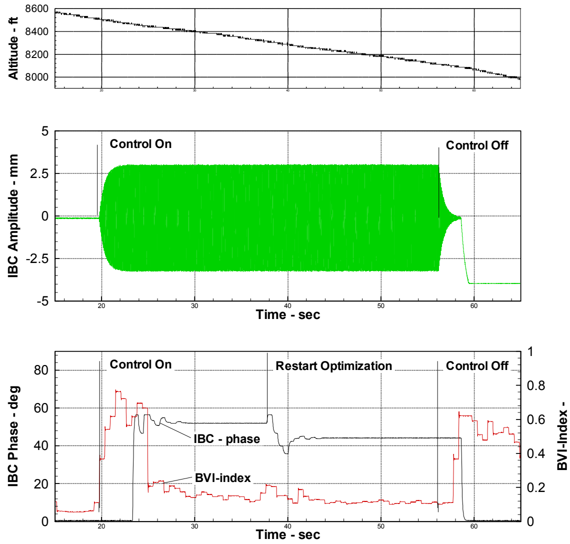


Fig. 21: Closed loop BVI noise reduction at descent flight with 600ft/min

To verify this result the values of the Kulite pressure transducers (0.97R, 3% chord) without IBC in Fig. 22 and with IBC in Fig. 23 are compared next. The reduction of the typical BVI spikes on the advancing blade side is obvious by using IBC feedback control.

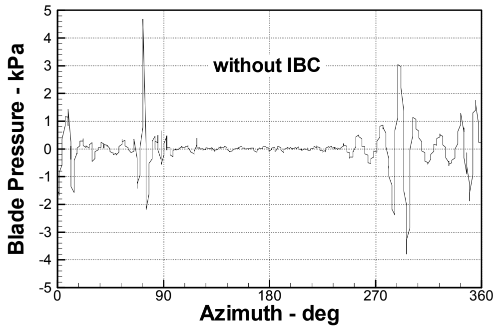


Fig. 22: Kulite pressure transducers without IBC (6° descent @ 65 kts)

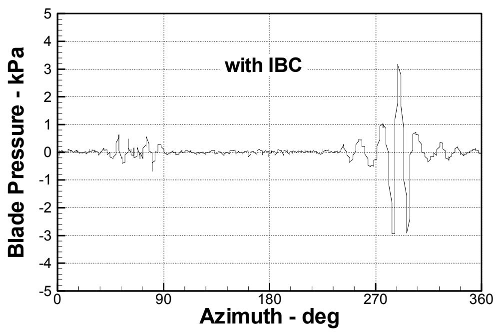


Fig. 23: Kulite pressure transducers with IBC feedback (6° descent @ 65 kts)

After this very encouraging result a new test with two control law variables (phase and amplitude) have been performed. The results for the 600 ft/min descent flight are comparable to those of the first control law. The results of a descent flight at 800 ft/min corresponding to a slope angle of approximately 8° are shown in Fig. 24. In this case the BVI noise reduction algorithm works very well again and the BVI-index could be reduced effectively. Similar to the first flight test an optimum amplitude and actuator phase for the 2/rev actuation is found in the first quarter of the advancing blade side (about 70° IBC phase @ 0.6° IBC pitch).

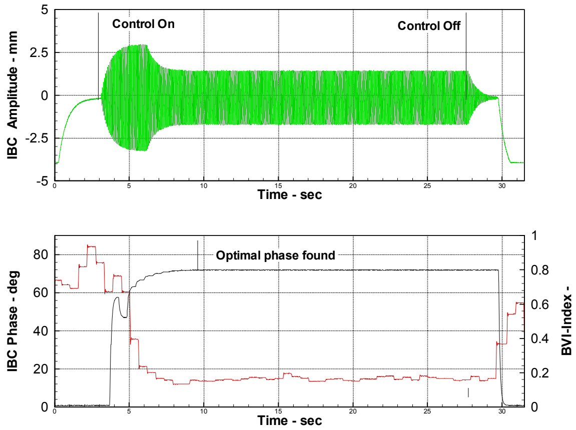


Fig. 24: Closed loop BVI noise reduction at descent flight with 800ft/min

In order to determine the controller behaviour under varying flight conditions further tests have been prepared and performed. A typical test flight starts with level flight at 65 kts, followed by descent flight conditions with (600 to 800) ft/min and ends with the recovery to level flight. The results are gathered in Fig. 25. It can be recognised that with increasing rate of descent the BVI-index is growing up, too, and the IBC computer starts the 2/rev noise control. In the following sequence the control algorithm is obviously not able to find a stable solution for the optimum IBC phase and amplitude in this transient flight state, but nevertheless a reduction of the BVI noise emission is achieved. During the recovery the optimum IBC phase and amplitude values converge leading to a minimised BVI-index. At test time 105 sec the control algorithm is switching to the idle state because no more BVI noise is detectable. This control behaviour will now be adapted and optimized by changing the controller parameters and gains in order to improve the transient behaviour of the control system. In addition, other closed loop BVI noise control concepts are prepared and will be flight tested using blade pressure data for BVI detection and feedback (Ref. 11).

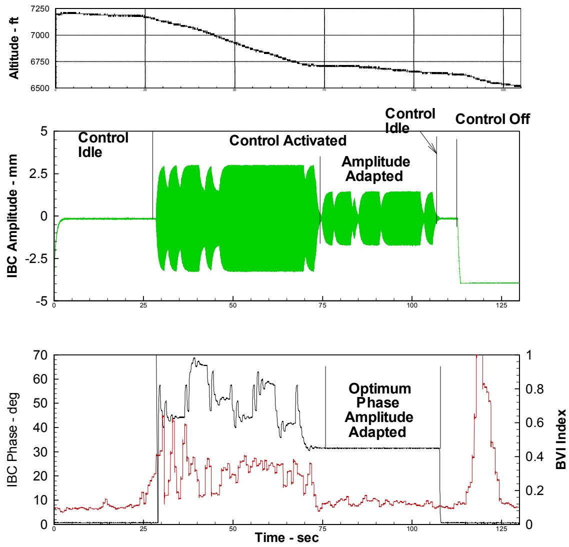


Fig. 25: BVI noise reduction under varying flight conditions

5 Vibration Control

The potential to efficiently control vibrations has been of major concern for exploration already in the earliest stage of HHC/IBC activities (Ref. 5, 12). In this context, the BO 105 S1 flight test campaigns have indicated that hub loads and airframe vibrations are efficiently controllable by IBC input stimulation (Ref. 13). Fig. 26 and Fig. 27 show time histories of vertical vibrations in the vicinity of the BO 105 co-pilot's seat without IBC input and with limited authority IBC input, respectively. A spectral analysis reveals a significant decrease of the measured 4/rev vibrations by application of open loop IBC control (IBC frequency 4/rev, pitch amplitude 0.4°). Nevertheless, the small actuator authority chosen for safety reasons in the early time of IBC flight testing have posed a serious barrier preventing the possibility to reduce 4/rev hub loads or vibrations to a high grade.

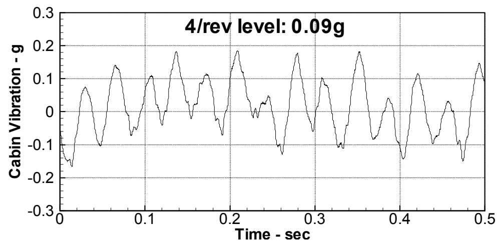


Fig. 26: Vertical cabin vibrations at level flight 110 kts without IBC

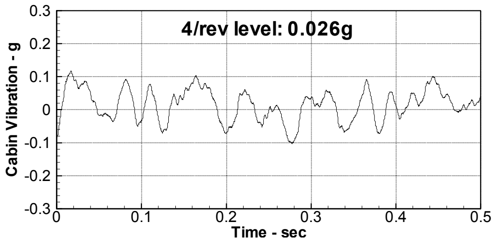


Fig.: 27: Vertical cabin vibrations at level flight 110 kts with IBC on

5.1 Vibration Control Concept

During various test campaigns and related theoretical investigations (Ref. 14), one has noticed that the relationship between IBC input and generated hub loads/accelerations is very sensitive with respect to test conditions (e.g. flight/wind speed). This sensitivity has consequently lead to the demand for a closed loop system for efficient vibration control by feeding back the vibrations as error signals. Due to the limited real time computer power available in the past decades, focus has been given on "slow" vibration control algorithms formulated in the frequency domain. Nowadays, commercial real time systems offer the possibility to use advanced time domain algorithms allowing sampling rates up to 100 kHz which are sufficiently high for resolution compared to 4/rev vibration signals (approximately 28 Hz in the case of BO 105). Regarding vibration control, the usage of three actuation channels for system inputs leads to a multiple input multiple output (MIMO) system allowing the control of three independent targets (appropriate controllability assumed). Advanced control theory provides a large variety of strategies for MIMO control designs in the time domain. Regarding the special characteristics of vibration – almost linear plant behaviour due to small amplitudes – the principle of disturbance rejection is of first choice for the reduction of the hub load excitations and/or accelerations. Due to the difficulties in measuring rotor states, an output feedback scheme is advantageous for feedback purposes.

In order to account for robust control properties, dynamic compensators (servo-compensators) derived from the internal model principle (Ref. 15) are implemented in the feedback loop. The dynamic compensators are realised as notch filters (design frequency 4/rev in the fixed/airframe system) for modelling the sinusoidal nature of the disturbances at 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 varying rotor speeds by online adaptation.

Fig. 28 displays the structure of the vibration controller for the case of hub load feedback (Ref. 16). 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 on-blade sensor and actuation control data. The application of multi-blade coordinates offers additionally 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.

Beside the transformation blocks between fixed and rotating systems, 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. Thus, a pure experimental approach for the determination of the gain matrix seems not appropriate. From a theoretical point of view, advanced controller design procedures like optimal output feedback (linear quadratic output feedback) allows 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. In Ref. 16, an approach is presented featuring lowered requirements of plant characteristics knowledge. A semi-empirical procedure has been applied based on phase dependencies within the feedback loop.

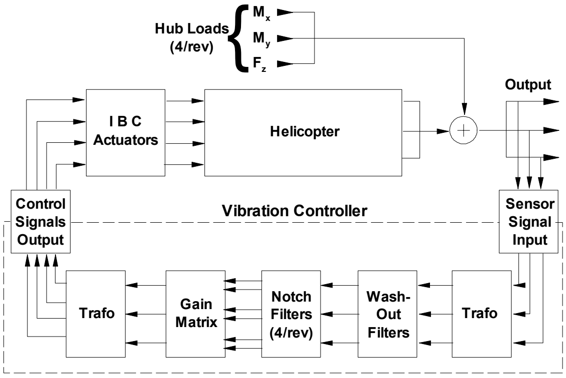


Fig. 28: Block structure of the vibration control feedback loop

5.2 Simulation of the vibration controller

Fig. 29 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 revolutions. Nevertheless, a shock in the control system is 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.

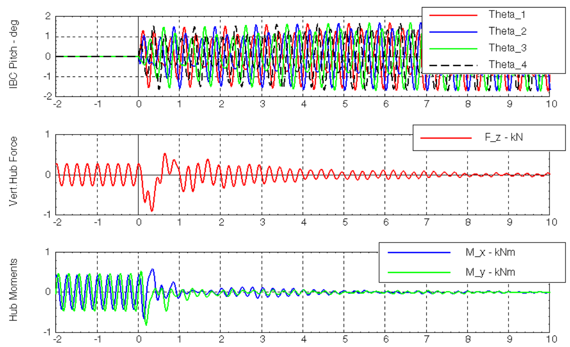


Fig. 29: Simulation of vibration controller activation under perfect conditions

For the assessment of the vibration controller under operational conditions, the (perfect) excitation signals of the periodic hub loads are superposed with a simple noise model (4/rev disturbances). The variances are selected at least one order higher than expected due to former flight test results. Fig. 30 demonstrates the ability of the vibration controller to deal with this type of disturbed excitation signals without unstable tendencies. Due to the extreme narrowband characteristics of the notch filters, disturbances of lower or higher frequencies are likewise of no concern for the correct functionality of the vibration controller.

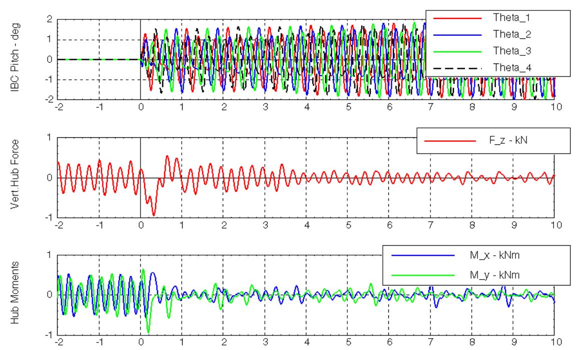


Fig. 30: Simulation of vibration controller in disturbing environment

The prepared vibration disturbance rejection controllers will be flight tested soon.

6 Conclusions and Outlook

The development of IBC technology – having a long tradition in Germany by co-operation of ECD, EADS, DLR and ZFL – is now culminating in an extensive closed loop flight testing program of the BO 105 S1 demonstrator. This paper covers recent experimental and theoretical activities of the research program with emphasis on the following topics :

- Modification of the demonstrator for the special requirements of feedback control by updated hard- and software e.g.
  - integration of an embedded controller
  - improved IBC actuation bandwidth
  - upgrade of safety concept/systems
- Modular control architecture for simultaneous BVI noise and vibration control
- Evaluation of appropriate BVI detection methods and BVI-index definitions for feedback noise control regarding
  - skid-mounted outboard microphones
  - Kulite pressure transducers on rotor blade
  - piezofilm detection system on rotor blade
- Verification of feedback control concept for BVI noise by closed loop flight tests starting with microphone signal feedback which shows good results for BVI noise reduction in descent flights
- Presentation of an advanced vibration control concept in the time domain including comprehensive simulations for hub load reduction in level flight

The IBC research activities within this project aim on a widespread commercial application in future helicopters. The outcomes of the related studies will be transferred to next generation concepts, e.g. active flaps. Therefore, the IBC program will continue with the following short and medium term activities:

- Improvement of current noise controller configuration concerning transient behaviour
- Testing of more advanced BVI noise control concepts including sensor systems in the rotating system (Kulites, piezofilm)
- Flight testing of the prepared vibration controller
- In-flight testing of the BK117 testbed equipped with active trailing edge flaps for individual blade control

The developed piezo-active flap units with displacement amplification and push-pull mechanism are shown in Fig. 31.

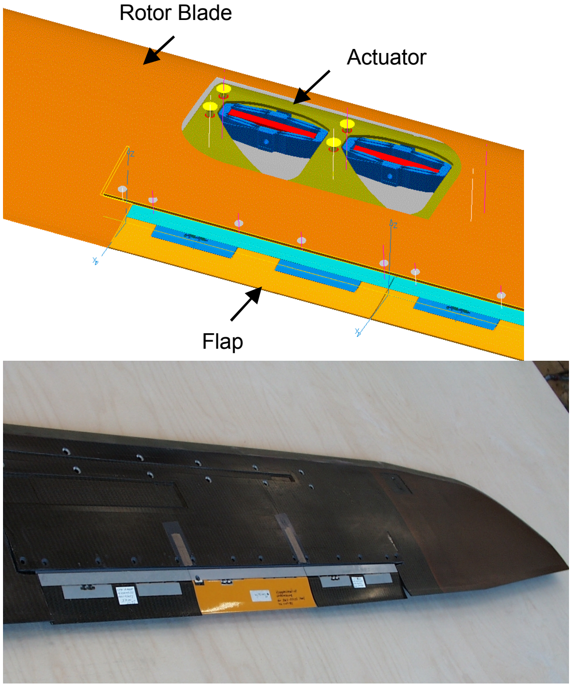


Fig. 31: Piezo-electric driven blade flaps for noise and vibration control

The system is already successfully tested under laboratory conditions and will be flown on the BK117 next year.

7 Acknowledgement

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