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The Role of Active Control in Future Rotorcraft

D. Teves, G. Niesl
EUROCOPTER
DEUTSCHLAND
München, Germany

A. Blaas
ZF LUFTFAHRTTECHNIK
GmbH
Kassel, Germany

S. Jacklin
NASA Ames Research
Center
Moffet Field, USA

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Abstract

In order to increase the helicopters share in future air-traffic, its efficiency, its reliability and its public acceptance have to be improved. Therefore the key design goals are the reduction of weight, fuel consumption, cabin vibrations, noise levels and maintenance costs.

In the last decades big progress has been made by using modern aerodynamic and structural blade designs, modern engine technologies and composite materials. Additional improvements can be achieved by application of active rotor control technology investigated by several helicopter manufacturers and research institutions. Besides the integration of actuators below the non-rotating part of the swashplate (HHC), it is also possible to control each blade individually by actuators replacing the pitch link in the rotating system (IBC). At Eurocopter both systems (HHC and IBC) have been designed and tested. An efficient realisation of an experimental IBC-system has been achieved by ZFL in co-operation with ECD. Several flight and wind tunnel tests with IBC were carried out since 1990 on a BO105 helicopter and in the 40 ft by 80 ft wind tunnel at NASA Ames. The potential of HHC has been investigated in flight at ECF on a Gazelle helicopter between 1985 and 1988.

Based on this experience the role of rotor active control will be analysed in this paper. The most important questions to be addressed are:

- What are the benefits of currently investigated rotor active control technologies?
- What are the penalties of these technologies with emphasis on weight, energy, maintainability?
- What are the possibilities for further improvements?
- What is the potential of servo-flaps, smart materials, improved control-technologies etc.?

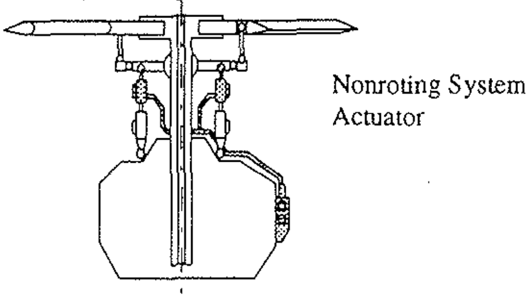
In order to answer these questions, the results of Eurocopter's recent rotor active control investigations will be reviewed and discussed. Based on the current system design the effort with respect to the weight, power consumption and manufacturing costs will be estimated and compared with conventional technologies. Furthermore results of various flight- and wind tunnel tests will be discussed in order to demonstrate the benefits of rotor active control technology .

Based on this knowledge, an assessment of the current status of active rotor control technologies will be performed, and claims for future developments and applications will be derived.

1 Introduction and Definitions

A major improvement of helicopter performance and comfort can be achieved by implementation of rotor active control technologies. The scope of this paper is limited to methods which directly influence rotor aerodynamics by angle-of-attack changes that are introduced by active control of the blade torsion. In case of an Individual Blade Control (IBC) system each blade is controlled individually by pitch-link actuators or servo-flaps for instance. In contrast to IBC a Higher Harmonic Control (HHC) system is characterised by implementation of actuators below the swashplate (see Fig. 1).

HHC by Swashplate Actuation



IBC by Pitch-Link Actuation

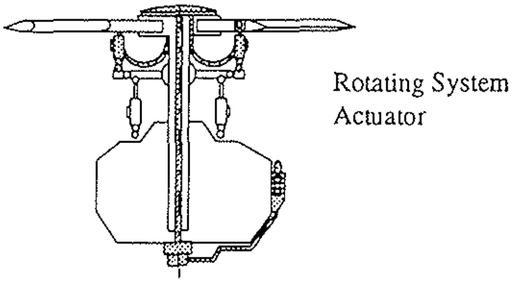


Fig. 1: Active Blade Pitch Control Concepts:
HHC vs. IBC

Table 1 : Controllability of Rotor Harmonics by Rotor Active Control

Rotor Modes		**Rotor Harmonics**			**Remarks**
		3 Blades	**4 Blades**	**5 Blades**	
reactive *)	collective	3/rev, 6/rev	4/rev	5/rev	modes controllable by HHC & IBC
	progressive cyclic	2/rev	3/rev	4/rev	
	regressive cyclic	4/rev	5/rev	6/rev	
reactionless	difference	-	2/rev	-	modes controllable only by IBC
	progressive wobble	-	-	3/rev	
	regressive wobble	-	-	2/rev, 7/rev	

*) Modes couple with nonrotating system

With the three swashplate control degrees of freedom (collective and two cyclic), it is possible to achieve individual blade pitch control only for rotors with up to three blades. Consequently the blade pitch control capabilities of HHC and IBC do not differ in this special case.

In any event, both HHC and IBC must create a pitch control law which is phased appropriately for each rotor blade. For an N-bladed rotor operating in a steady state flight condition at the main rotor rotational speed Ω, the pitch waveform has to be identical for each blade. In case of HHC this behaviour is only achievable, if the swashplate is excited at integer multiples i of the blade passage frequency ($N\Omega$).Table 1 shows the controllability of rotorharmonics by rotor active control. Thus with HHC only a special selection of rotor harmonics $i\,N\,\Omega$ and $(i\,N \pm 1)\,\Omega$ can be controlled which corresponds to the reactive rotor modes.These modes are responsible for the dynamic hub loads that are transferred from the rotor to the nonrotating system (airframe). The reduced control capability of HHC is obviously sufficient for controlling the vibratory excitation of the airframe. Furthermore it can be concluded that for other rotor active control tasks which require an arbitrary blade pitch waveform (including the control of the reactionsless rotor modes) an IBC system is needed (Ref. 1,2,3).

Rotor Active Control - Benefits

A short overview about the potential of rotor active control is given in Fig. 2 which is discussed below.

- The **vibration reduction** capability of HHC and IBC gives the designer the opportunity to eliminate other vibration reduction devices.

- The capability of HHC and IBC to reduce the helicopters **noise radiation** may enable the operator to fly in regions which were restricted for helicopter operations due to noise limitations. In case of military applications noise reduction helps to hinder the detection of the aircraft.

- **Aerodynamic improvements** introduced by IBC may allow an expansion of the helicopters flight envelope or an improvement of the rotor performance.

- There exists a wide range of applications in order to improve the rotors transient behaviour and damping characteristics. Due to this **stability augmentation** capability it may be possible to eliminate lead-lag dampers or to prevent stall flutter.

Reasons explaining the different potentials of HHC and IBC will be discussed in the following sections of this paper. Summarising all the beneficial effects mentioned above it can be concluded that rotor active control has a very wide range of applications in nearly all disciplines of helicopter design. This fact makes it unique compared with other systems implemented in the aircraft, who only have one specific task. An important question arising in this contents may be: Is it possible to fulfil several of these tasks simultaneously? The answer to this question will be one major topic of this paper.

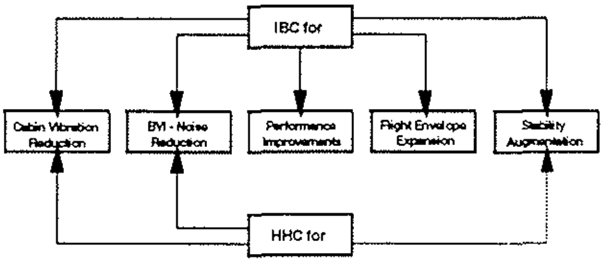


Fig. 2 : Rotor Active Control Potential

Rotor Active Control - Penalties

Up to now the beneficial effects of rotor active control were discussed. Of course it is also necessary to mention the penalties introduced by the weight of such a system and its power consumption. Furthermore it has to be realised that the amount of complexity added to the helicopters control system is quite different in case of HHC and IBC.

This increase of complexity is obviously opposing the current trend of modern rotor system design (Ref. 4). In order to reduce the helicopters maintenance and production costs large effort has been made by several manufacturers in order to reduce the complexity of the rotor-system by eliminating bearings, hinges and lead-lag dampers. The additional cost introduced by an HHC or IBC system can therefore only be accepted, if the potential of such a system leads to an increase of the helicopters productivity and an expansion of its operational characteristics.

In case of an HHC system most of these difficulties are probably less severe. Theoretically it can be realised by using the existing primary control actuators. The amount of complexity added to the helicopter design seems therefore to be comparatively small. Consequently a comparison of the potential and penalties of IBC and HHC will be one of the important topics of this paper. The basic question in this content may be: Are the existing hydraulic hardware realisations of current systems sufficient in order to compete with other design solutions or is it compulsory to look for new actuation concepts such as smart material designs.

Intention of the Paper

Furthermore it has to be admitted that there exists a number of unsolved problems associated with the control algorithms which have to be addressed. One major prerequisite in order to find an appropriate solution is the understanding of the complex physical phenomenon with respect to rotor active control. Although encouraging results have been achieved in the vibration reduction task, other applications like noise reduction and stall delay are still object of intensive experimental and theoretical research.

The intention of this paper is to give an overview concerning past and future research activities of Eurocopter, ZFL, DLR and other partners. The theoretical background of the various control problems is explained and discussed on the basis of own investigations and the results of several other research institutions as well. Based on this knowledge, an assessment of the current status of active rotor control technologies will be performed, and claims for future developments and applications will be derived.

Definitions and Conventions

Next some definitions and conventions will be explained which are used below. The rotor azimuth-angle ψ defines the azimuth position of the reference blade with respect to the orientation of the free-stream velocity. The periodic time history $x(\psi)$ of measured rotor signals is described by the fourier series expansion

$$x(\psi)=a_0+\sum_{i=1}^{\infty}a_i\cdot\cos(i\cdot\psi-\varphi_i)$$

where a_i is the amplitude and φ_i is the phase of the i^{th} harmonic. Instead of referring to the phase φ_i it is sometimes more convenient to use the corresponding azimuth position $\Delta\psi_i$

$$\Delta\psi_i=\varphi_i/i \qquad \text{for the positive halfwave}$$
$$\Delta\psi_i=(\varphi_i+\pi)/i \qquad \text{for the negative halfwave.}$$

The blade pitch angle defining the IBC control input is positive when the leading edge moves upwards.

2 Current Rotor Active Control System Design

Up to now all rotor active control technologies were based on blade root pitch control, which is achieved by hydraulic actuators. At Eurocopter both HHC and IBC systems have been designed and tested.

HHC System of ECF

According to the discussion above a HHC system is realised by using actuators below the swashplate. An experimental system for the 3-bladed rotor of the Gazelle helicopter was flight tested at ECF (Ref. 5). In addition a HHC system design for the NH90 helicopter (Ref. 6) has been investigated at ECF extensively.

IBC System of ECD/ZFL

An IBC-system was investigated at ECD in cooperation with ZFL (Ref. 7). It is realised by replacing the rotating control rods by hydraulic pitch-link actuators. As mentioned before, several flight and wind tunnel tests were carried out with different IBC prototypes on a BO105 helicopter at ECD (Ref. 7, 8) and in the 40 ft by 80 ft wind tunnel at NASA Ames (Ref. 9-12) respectively. Fig. 3 gives more details about this system.

The actuators operate hydraulically and are controlled by servovalves. In case of hydraulic pressure loss, the actuators are locked by springs in a definite position and act like conventional pitch-links. A hydraulic slipring located below the gearbox is used in order to transfer the hydraulic power from the non-rotating power supply system through the shaft to the hub. From there the servovalves of each blade are connected by flexible pipes.

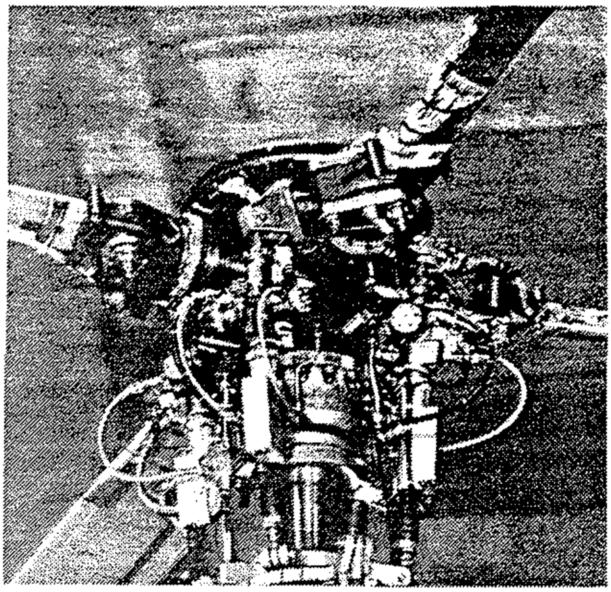


Fig. 3: Experimental IBC System (Bo105)

Controller Design

Another important topic is the controller design, which greatly determines the performance of the whole IBC system. Although it is beyond the scope of this paper to explain different approaches for each IBC task in detail, it is still useful to give a rough overview about the control strategies investigated up to now. In any case it is the task of the IBC controller to calculate the appropriate IBC control inputs. This is achieved by a feedback of measured quantities related to the specific control problem. For example vibration signals are fed back in the case of vibration control.

Frequency vs. Time Domain Control

Frequency domain control as well as time domain control have been investigated by several scientists for IBC applications. The basic differences of these algorithms are discussed below.

In case of the frequency controller a steady state operating condition and a quasi-steady dynamic rotor behaviour is assumed. This means that the rotor response as well as the IBC control inputs are periodic. The control law can therefore be expressed in terms of the fourier coefficients of the rotor response and the resulting IBC control inputs. Consequently a harmonic analysis and a harmonic synthesis is needed in order to implement the frequency domain controller.

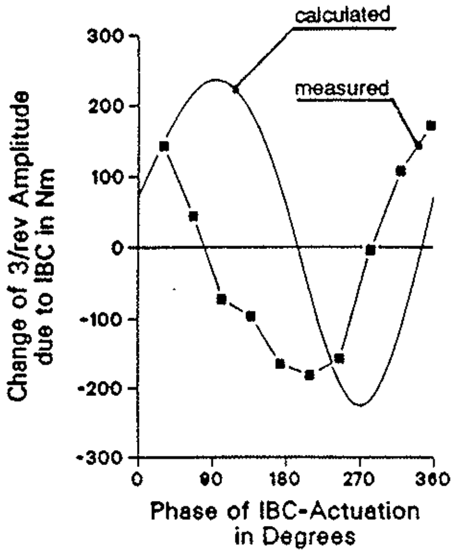
In case of time domain control the operating condition does not need to be steady and a realistic representation of the dynamic response behaviour of the rotor is essential for the control design. Furthermore with a time domain controller the stability of the system can be improved by an appropriate feedback gain. Such means of system stabilisation are not only beneficial for the damping characteristics of the rotor but can also be used in order to achieve a quick adaption to sudden changes of the aerodynamic excitation for disturbance rejection control tasks. Since a helicopter is often operating in unsteady flight conditions, such a high response characteristic of the controller is highly appreciated for future rotor active control-systems.

Dynamic Properties of the Rotor System

The main reason why frequency domain control was preferred up to now for rotor active control applications is associated to the complex dynamic behaviour of the rotor discussed below.

Direct Coupling

3/rev IBC Input → 3/rev Response



Interharmonic Coupling

4/rev IBC Input → 3/rev Response

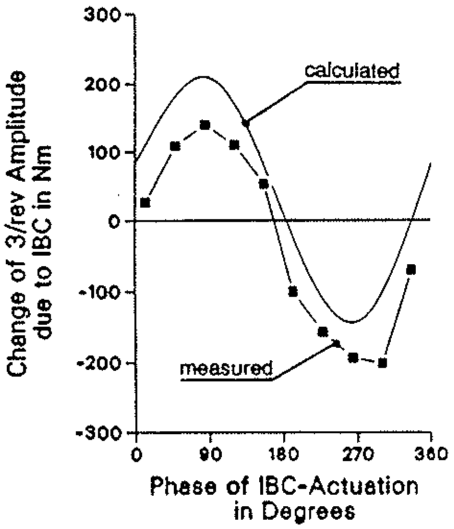


Fig. 4: Direct and Interharmonic Couplings by IBC (Bo105 Shaft Bending Moment at 61kts)

Experimental investigations have shown (Ref. 8) that the structural blade and rotor response due to a single-harmonic IBC input also contains harmonics which differ from the original excitation frequency. The origin of these inter-harmonic couplings is partly due to dynamic pressure variations which increase with the helicopters advance ratio. These variations are modulating the single harmonic angle-of-attack variations due to IBC resulting in multi-harmonic lift variations. Furthermore the circulation variations introduced by IBC produce inflow and angle-of-attack variations. Flight tests performed at ECD have proven that strong inter-harmonic couplings even exist at low flight speeds (see Fig. 4). Theoretical investigations based on an aeroelastic rotor model with free wake geometry (Ref. 13) show that the phenomenon of inter-harmonic couplings can be investigated adequately with modern rotor analysis tools.

Frequency Domain Representation of Rotor Dynamics

In case of frequency domain control (Ref. 14,15) the dynamic behaviour of the rotor is expressed by a linear relation between the fourier coefficients of the control inputs u and the rotor response y in terms of a T-matrix:

$$y = T \cdot u$$

Inter-harmonic coupling can therefore easily be represented as cross-coupling coefficients in the T-matrix. The identification of the T-matrix can be done experimentally. Flight tests at ECF have demonstrated that an in-flight identification of the T-matrix based on a Kalman-filter-technology (Ref. 15) is feasible (Ref. 16).

Time Domain Representation of Rotor-Dynamics

In the time-domain, the phenomenon of interharmonic couplings is related to the time-variant properties of the differential equation describing the dynamic behaviour of the rotor system.

$$\dot{x}(t) = A(t) \cdot x(t) + B(t) \cdot u(t)$$
$$y(t) = C(t) \cdot x(t)$$

The changes of the dynamic response y(t) due to the rotor active control inputs u(t) are expressed here by a linear system with periodic time-varying matrices A,B,C (period is one rotor-revolution) and the state vector x. The controller design for these systems requires more sophisticated methods. The theoretical basis for this task is described in Ref. 17. The efficient application of output feedback control for rotorcraft problems including stabilisation are discussed in Ref. 18, 19.

Disturbance Rejection in Time Domain

Next some applications of time domain control will be discussed. Most of the rotor active control problems are very similar to the disturbance rejection problem of conventional linear control theory. A typical design goal is to reject sinoidal disturbances. These disturbances may be either the vibratory response of the airframe which are occurring at integer multiples of the blade passage frequency, or hub loads in the rotating frame where additional rotor harmonic frequencies are present. Furthermore it might be possible to reject non-harmonic oscillatory control loads as they occur in stalled flight conditions. Fig. 5 shows a standard block diagram for feedback compensation to reject a disturbance. The closed loop transfer function S(s) of this system can be written in case of a single-input single-output control as

$$S(s) = z(s) / d(s) = G_d(s) / \left(1 + K \cdot H(s) \cdot G_P(s)\right).$$

Consequently the disturbance d(s) is completely rejected from the output z(s) if S(s) is equal zero or if the controller transfer function H(s) is infinite at the oscillation frequency of the disturbance ω_d. This means that a conjugate complex imaginary pole-pair $\pm i \cdot \omega_d$ has to be included in the controller dynamics in order to realise an appropriate notch filter characteristic (see Fig. 6). A more general formulation of the disturbance rejection problem which includes multiple control inputs and outputs is denoted in classical control theory as the "Internal Model Principle". According to this theory the eigensolution of

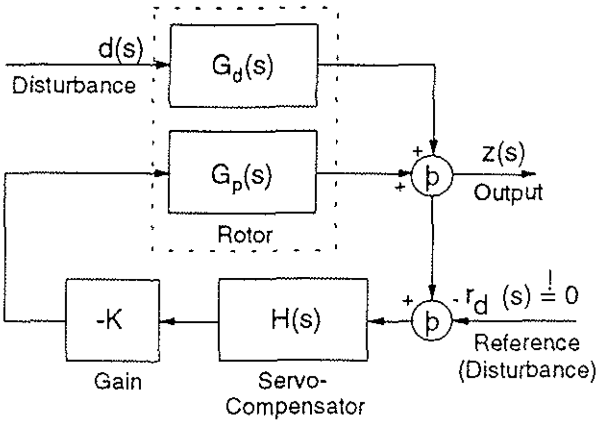


Fig. 5: Rotor Disturbance Rejection by Servo-Compensator

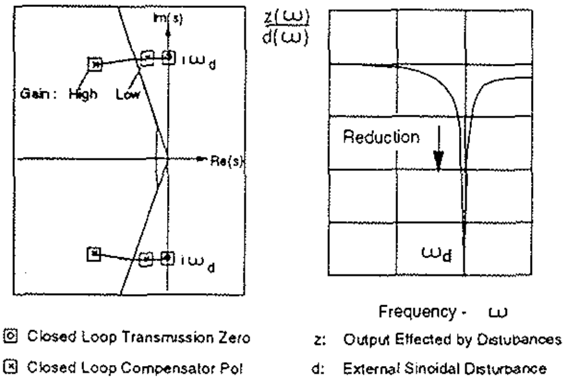


Fig. 6: Sinoidal Rotor Disturbance Rejection

Table 2: Basic Assumptions and Potential of Frequency vs. Time Domain Control

	Frequency Domain	Time Domain
basis of controller design	steady state operating conditions	steady and unsteady operating conditions
representation of control input and output	fourier coefficients	general time histories (using multi-blade coordinates if appropriate)
stability augmentation & improvement of response characteristics	not possible	possible
online system identification	possible	not yet investigated

the controller has to be a general description of the disturbance (ref. 20.) In case of a single-input single-output system and a sinoidal disturbance, the controller is therefore represented by an oscillator which is tuned to the disturbance frequency.

Although the disturbance rejection task S(s) = 0 is solved even for very low feedback gains K , high gains K are required in order to improve the transient behaviour of the controller. Fig. 6 indicates that an increase of the feedback gain K causes a left shift of the servo-compensator poles resulting in an increase of stability. In order to prevent instabilities due to high gains, an appropriate stabilising feedback is required.

Concluding Remarks
It can be concluded that the time domain approach implies a potential which is superior to the capabilities of conventional solutions based on the frequency domain approach, see Tab 2. The investigation of time domain control is one major research topic at ECD. First ideas concerning this matter will be discussed below.

3 Benefits of Rotor Active Control

Next the benefits achieved by application of rotor active control will be presented with emphasis on experimental results.

3.1 Vibration Reduction

The vibration reduction potential of HHC and IBC is reviewed first. Based on these results, preliminary conclusions can be derived concerning the controllers and the performance of future systems.

Test Results with Frequency Domain Control
The vibration reduction potential of HHC has been tested in flight on the Gazelle helicopter at ECF (Ref. 16). An adaptive frequency domain control algorithm was applied.

The results presented in Fig. 7 show significant vibration reductions. Furthermore the subject of HHC has been tested by many other researchers in wind tunnels (Ref. 21, 22, 23) and in flight (Ref. 24, 25).

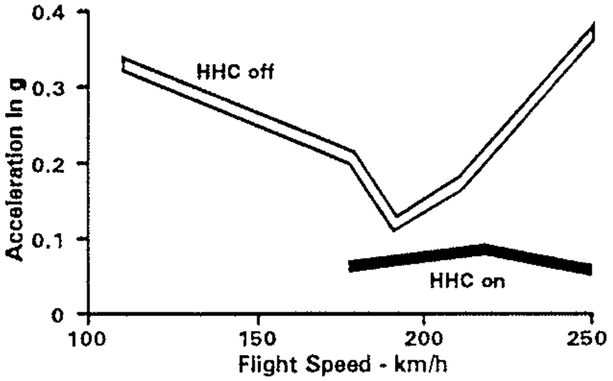


Fig. 7: Vibration Reduction by HHC: Closed Loop Flight Tests (Gazelle)

The effect of harmonic IBC control inputs on the cabin vibration level is presented in Fig. 8 derived from BO105 flight tests. Although the control authority was limited to 0.4°, a significant reduction of the cabin vibration level was achieved.

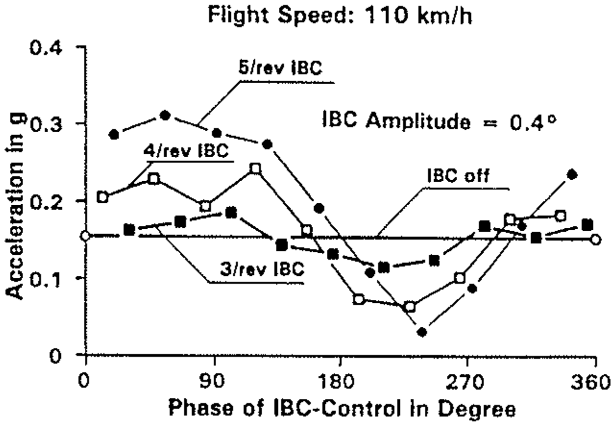


Fig. 8: Vibration Reduction by IBC Open Loop Flight Tests (BO105)

Vibration Reduction by Time Domain Controllers
The behaviour of an HHC time domain controller for vibration reduction was investigated at ECD and DLR (Ref. 26, 27) for the BO105 model rotor (scale 1:2,5). In order to get first information about the stability properties, a linear time invariant representation of rotor dynamics was applied using multi-blade coordinates and averaging procedures. A disturbance rejection approach as discussed above was the basis of the controller design (see Fig. 9).

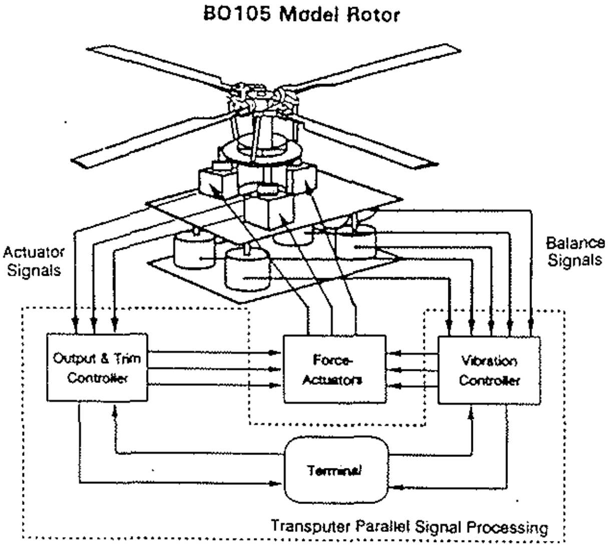

BO105 Model Rotor

Fig. 9: Vibration Reduction by HHC in the Time Domain (Principle)

The system response due to circular hub moment disturbance is shown in Fig. 10. The results indicate that the final steady state response can be reached quickly within two rotor revolutions. Similar results are published in Ref. 28 and 29. These very encouraging results are the basis of future IBC vibration reduction controller design activities at ECD.

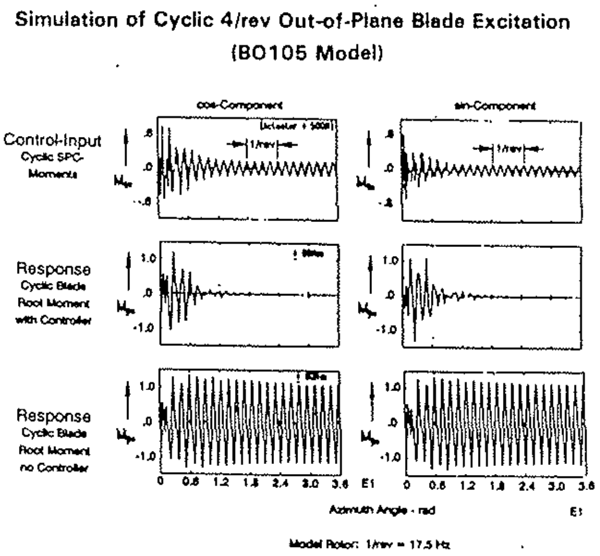

Simulation of Cyclic 4/rev Out-of-Plane Blade Excitation (BO105 Model)

Fig. 10: Vibration Reduction by HHC in the Time Domain (Simulation)

A schematic IBC vibration controller is presented in Fig. 11. The vibratory hub loads are eliminated here by disturbance rejection feedback. Several important subjects have to be investigated in order to find an optimal solution:

- Can we avoid independent controllers for each blade in favour of controlling the complete rotor system in the non-rotating frame as it is done in case of HHC ?
- Is it possible to use constant gains in the whole flight envelope or do we need an adaptive gain control concept ?
- Are constant gains adequate to the time-invariant dynamic characteristics of a rotor system or is it necessary to deal with periodic gains?

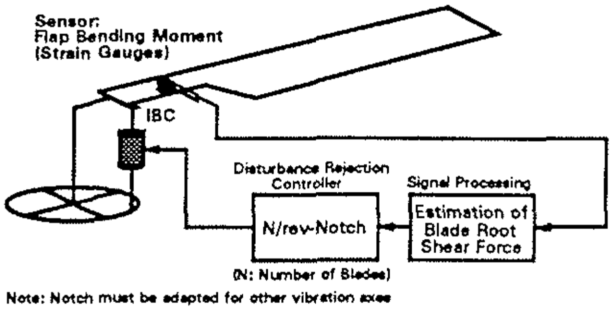


Fig. 11: IBC Concept for Vibration Reduction

3.2 BVI Noise Reduction

Very 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. By a higher harmonic control of the blade pitch it is possible to modify the misdistance between the tip vortex and the blade, the vortex strength, or the blade pitch at the position of blade vortex collision (Fig. 12, Ref. 30). In principle, there is no difference in the noise reduction mechanism between higher harmonic pitch control in the fixed system below the swashplate or in the rotating system.

Both concepts have been proved to be very effective for BVI noise reduction. Noise reductions up to 8 dB were measured by different single frequency input modes. Due to the complex dynamic behaviour of the blades, multi-harmonic input modes like small pulses were not as effective as expected.

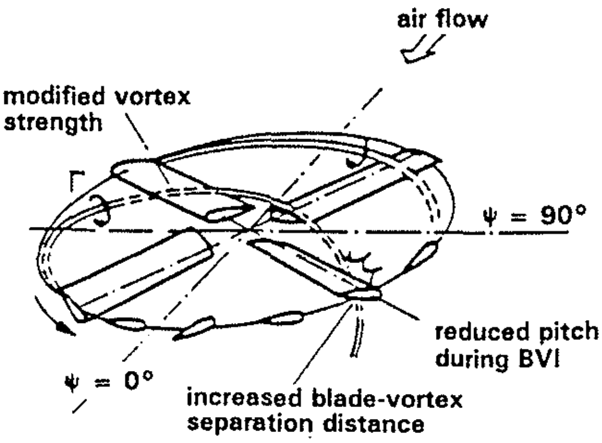


Fig. 12: Noise Reduction Mechanism by Rotor Active Pitch Control

A very comprehensive test of the effect of higher harmonic blade pitch control on the noise emission at various flight regimes was conducted by NASA Langley in the TDT wind tunnel with a BO105 model rotor (Ref. 31). Fig. 13 shows the areas of noise reduction with higher harmonic control inputs related to the baseline cases without control. As the measurements were conducted on the basis of sound power levels in a reverberant environment, the resulting levels are not comparable to results of other wind tunnel or full scale tests. However, the validity of the results has been proved by HHC tests in the German Dutch wind tunnel (Ref. 32).

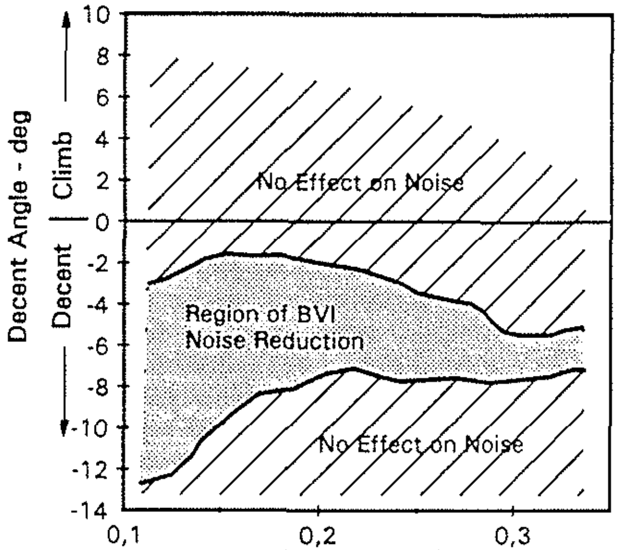


Fig. 13: Flight Condition & Possible BVI Noise Reduction by HHC (4/rev input mode)

Even if a flight condition inside the BVI noise radiation boundary is considered, the resulting noise reduction is highly dependent on the phase and amplitude of the higher harmonic blade pitch input. Fig. 14 (Ref. 31) summarises the noise results of the baseline case and the optimum HHC input phase versus the descent flight path (advancing side, $\mu=0.15$). As long as BVI noise is generated, noise reductions up to 6 dB can be observed.

All tests with flight condition variation indicated the need for a fast closed loop control system which is able to control the phase with respect to the BVI noise generation region. In view of the current knowledge, a control concept is needed at least for the advancing side. BVI noise reduction will be based on the identification of the azimuth region in the rotor disc where the BVI noise is generated. The crucial question is the definition of an appropriate sensor for the control system. The use of a microphone as a sensor turned out to be not feasible because the signal of a cabin mounted microphone is not directly related to the radiated BVI noise. There is noise radiation in other directions that is not heard in the cabin. Therefore, if the control system is on condition for lowest noise level at the cabin microphone, there might be still BVI noise radiated to a ground observer.

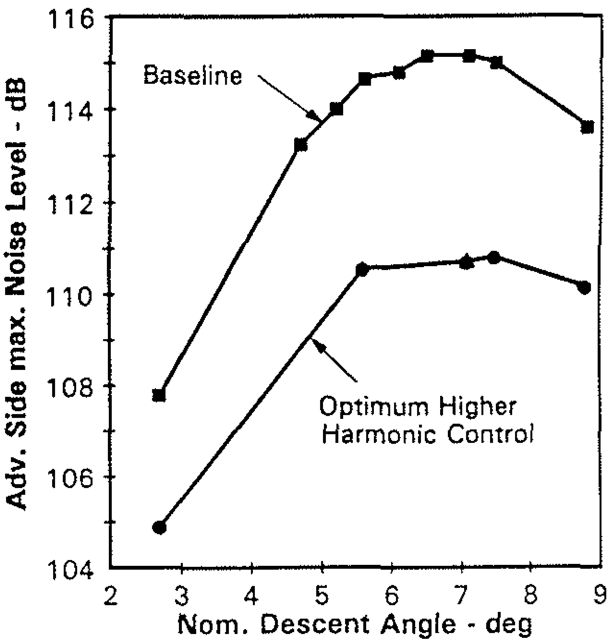


Fig. 14: BVI Noise Reduction vs. Descent Angle with HHC

The IBC full scale wind tunnel tests with the BO105 rotor (NASA Ames) clearly indicated that the optimum input phase for high BVI noise reduction can be directly related to the azimuth region where the blade vortex interactions occur. The principle can be seen from Fig. 15 for a 2/rev IBC-input. The measurements are valid for the advancing blade side using one fixed microphone position. The test conditions of Fig. 15 are defined by 6 deg. descent glide path angle and an advance ratio of 0.15.

A noise reduction is obtained if the blade pitch is changed at the azimuth position where the tip vortex collides with the following blade. Depending on the vertical position of the vortex relative to the blade the pitch angle has to be either increased or decreased. In addition, noise reduction is also obtained if the blade pitch is reduced at the azimuth angle where the corresponding tip vortex is generated.

The different effects of 2/rev IBC which were observed in the NASA Ames wind tunnel are gathered in Fig. 16. The BO105 wind tunnel results were verified for different harmonic inputs and correlated well with HHC test in the DNW.

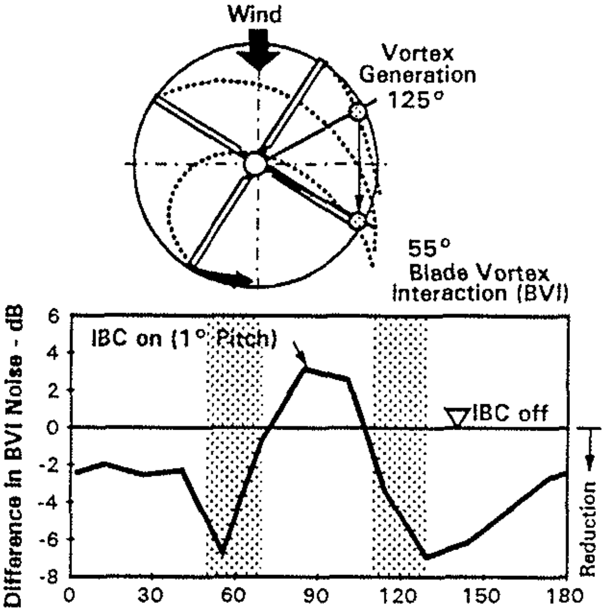


Fig. 15: Noise Reduction Potential of 2/rev IBC-Input with Varying Phase

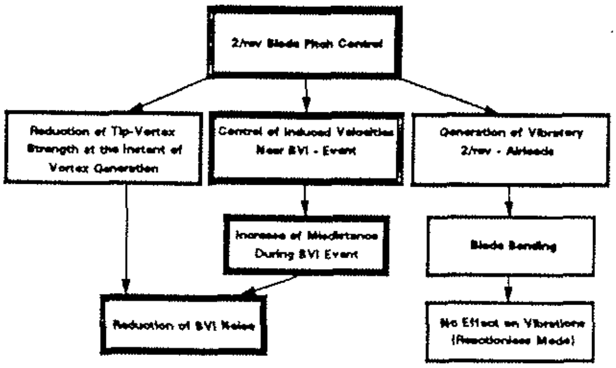


Fig. 16: BVI Noise Reduction by 2/rev IBC

Due to the various tests, a pressure sensor on the blade at about 80% radial section seems to be the most favourable sensor for the feedback control system. The use of the azimuth section implies a control system working in the time domain. A scheme of a control system for BVI noise reduction is given in Fig. 17. The feedback signal (blade pressure) will be processed by an appropriate filtering of the sound pressure level (SPL) with emphasis on BVI noise frequencies from 200 to 1200 Hz. Then the azimuth angle of the maximum BVI noise peaks will be determined by a Kurtosis analysis or a phase lock loop filtering. Subsequently, the control angle will be generated.

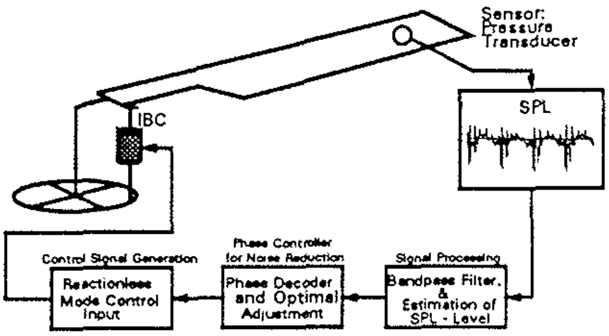


Fig. 17: IBC Controller Concept for BVI Noise Reduction

3.3 Simultaneous Vibration and Noise Reduction

High noise and vibration levels normally occur in low speed descent flight conditions, which are typical for a helicopter approach to a heliport. Hence a simultaneous reduction of vibration and noise should be considered as an important task of future rotor active control systems.

The potential of rotor active control with respect to simultaneous vibration and noise reduction has been investigated in wind tunnel for both HHC (Ref. 32,) and IBC (Ref. 11,12) on a 4-bladed BO105 rotor.

1. HHC tests of Fig. 18 where performed by the DLR in the German-Dutch wind tunnel DNW on a model rotor (scaling factor 2.5) using a frequency domain controller. In case of HHC two closed loop tests with and without vibration feedback were performed. The noise reduction obtained in both cases was about three dB. The results demonstrate that an increase of 4/rev hub loads due to noise control can be prevented by application of an additional vibration control loop. Anyhow an efficient simultaneous vibration and noise reduction could not be achieved with HHC.
2. IBC full-scale open loop test were performed in the 40 ft x 80 ft wind tunnel at NASA Ames. The results presented in Fig. 19 demonstrate that IBC obviously has the required potential of simultaneous noise and vibration reduction. A noise reduction of nearly 12 dB and 80% reduction of the 4/rev non-rotating hub loads were achieved by open loop testing. As explained in Fig. 16, the 2/rev noise control inputs generate reactionless hub loads which do not disturb vibration control.

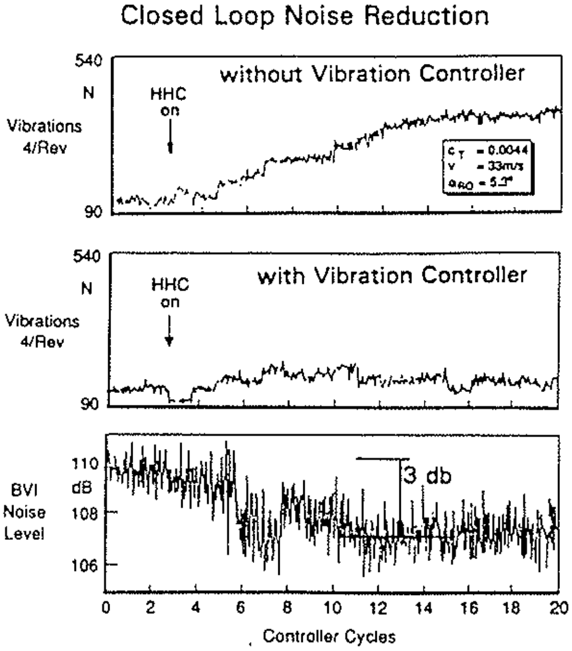

Closed Loop Noise Reduction

Fig. 18: HHC Tests with Noise and Vibration Control

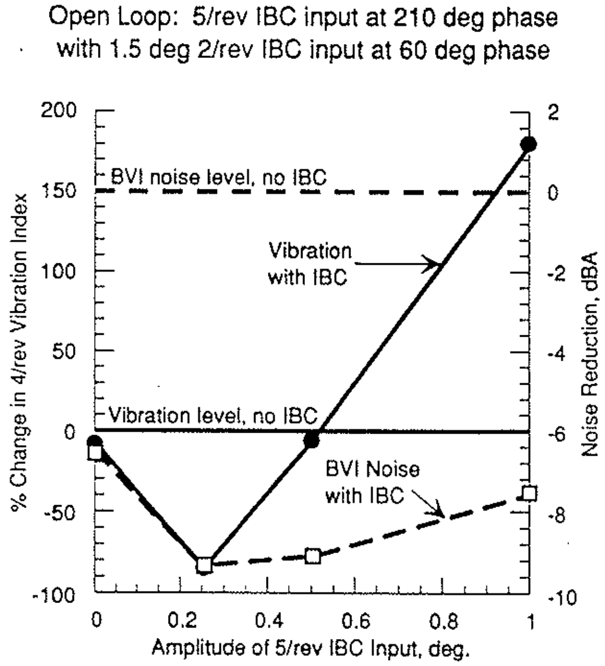

Open Loop: 5/rev IBC input at 210 deg phase with 1.5 deg 2/rev IBC input at 60 deg phase

Fig. 19: IBC Tests with Simultaneous Vibration and Noise Reduction

Thus a promising approach in order to establish a closed loop IBC controller for simultaneous noise and vibration reduction for the 4-bladed rotor is to use 2/rev control inputs for noise reduction and 3/rev, 4/rev and 5/rev control inputs for vibration reduction. Due to this frequency separation of the two control tasks, efficient vibration and noise controllers can be established.

In future closed loop simultaneous vibration and noise reductions will be one important research subject at ECD.

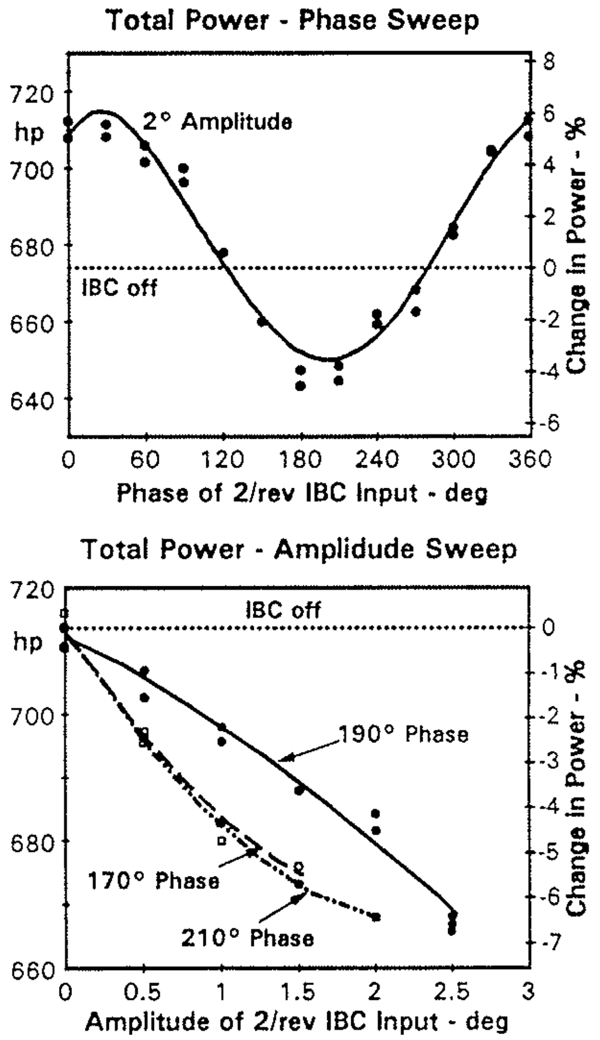
3.4 Performance Improvements and Expansion of the Flight Envelope

An important objective of IBC is to reduce the rotor power consumption and to extend the helicopters flight envelope. Both a reduction of fuel weight and an increase of the flight speed can lead to considerable improvements of the aircraft's productivity (Ref. 33).

IBC provides a means of directly controlling the angle-of-attack distribution and thus the airloads acting on the blade. Consequently performance improvements and the expansion of the flight envelope are a specific tasks of IBC and cannot be achieved with conventional HHC. By application of appropriate IBC controls it should be possible to avoid stall regions at the retreating side or to reduce the compressibility effects at the advancing side of the rotor disk.

Performance Improvement by Reduction of the Airfoil Drag on the Advancing Side

The potential of IBC alleviation of compressibility effects is demonstrated by tests on the Bo105.

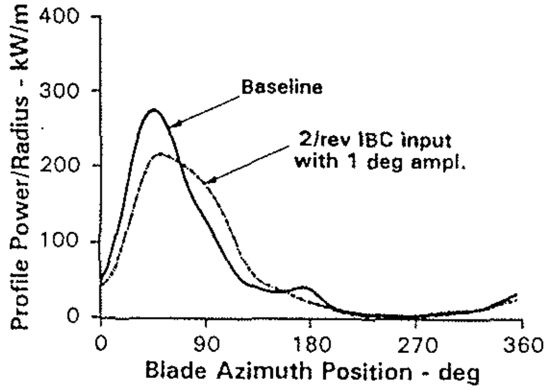

Total Power - Phase Sweep

Total Power - Amplidude Sweep

Fig. 20: Power Reduction by 2/rev IBC Pitch Control at High Speeds (Advance Ratio 0.4)

The benefits of IBC for reducing the airfoil drag on the advancing side were investigated in some detail during the NASA Ames wind tunnel tests with the BO105 rotor system at a high advance ratio of 0.4 and a thrust coefficient of $C_T/\sigma=0.075$. Due to load limitations of the test rig, the performance investigations were focused on level flight conditions at high speeds. The basic idea was to reduce the disk loading at the advancing side of the rotor in order to avoid drag divergence effects occurring at high machnumbers. A 2/rev IBC input was used in order to achieve the appropriate angle-of-attack changes. The result of an amplitude and phase sweep on the rotor shaft power is shown in Fig. 20 for fixed trim values of the propulsive force, the thrust and cyclic flapping. The power minimum occurring near a phase of 180° is associated with an angle-of-attack reduction at the advancing side of the rotor and thus causing a reduction of drag-divergence due to compressibility effects. The plots of Fig. 20 show that power reductions above 7% are possible if the IBC control amplitude exceeds the maximum actuator limit of 2.5°.

Profile Power Distribution vs. Azimuth



Effective Angle of Attack vs. Azimuth

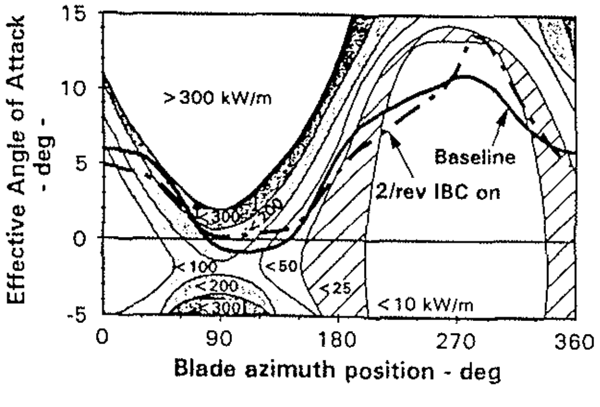


Fig. 21: Profile Power Reduction due to 2/rev IBC at High Speeds ($\mu=0.4$) Analysed for the Blade Tip (r/R=0.9)

Fig. 21 shows the effective angle-of-attack vs. blade azimuth position. The results where derived from two chordwise spaced accelerometers. Furthermore the plot shows lines of constant profile power distribution which can be calculated from the 2D-airfoil characteristics (Ref. 11). The measured 5% power reduction at 1° IBC inputs is therefore explained mainly due to the more favourable angle-of-attack curve in the first quadrant of the rotor disk at the blade tip. One major problem which might prevent further improvements is the shift of the negative angle-of-attack "half-wave" near 90° azimuth position (trim requirements).

Expansion of the Flight Envelope by Avoiding Stall Effects at the Retreating Side

Up to now the capability of IBC for improving the helicopters flight performance in high-speed level flight was demonstrated. Further investigations performed by several authors are denoted to an expansion of the helicopter's flight envelope. A number of severe physical problems due to stall occur when the rotor approaches the operational limits: The retreating blade generates high frequency torsional oscillations due to negative aerodynamic damping effects, and the rotor shows a pitch-up tendency accompanied by controllability problems.

Thus the stall flutter phenomenon causes a severe increase of the control system loads, which are in many cases the main limitations of the helicopter with respect to an expansion of its flight envelope. Consequently the alleviation of stall flutter by rotor active control is an additional requisite in order to extend the helicopter's flight envelope.

First successful experimental closed loop investigations at high thrust conditions have been published in Ref. 34 and 35 where an encouraging reduction of the rotor shaft power of 8% was achieved at an advance ratio of 0.3 and a thrust coefficient of $C_T/\sigma = 0.10$. by application of the new "stall flutter barrier" control concept. Further analytical results have shown that power gains of more than 17% should be possible in the extended region of the flight envelope. According to simulation results the control law used had a beneficial effect on both the rotor flapping stability and handling qualities. The "stall flutter barrier" control concept should be further investigated and applied in flight.

Future activities of ECD concerning stall flutter suppression will be focused on a time domain control approach shown in Fig. 22. Both a reduction of the pitch link loads and an increase of the torsional blade damping can be achieved by pitch rate feedback and by application of a disturbance rejection controller which is tuned to the "spike" torsional frequency.

It can be expected that this approach also has a beneficial effect on the rotor aerodynamics, because increased angle-of-attacks due to stall flutter oscillations are prevented.

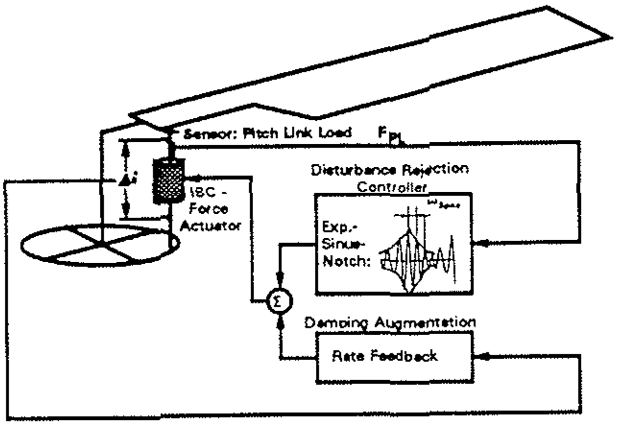


Fig. 22: IBC Concept for Stall Flutter Suppression

3.5 Stability Augmentation by Rotor Control Technologies

The subject of stability augmentation is related to many applications on the helicopter, such as the phenomenon of air- and ground-resonance, and various aeroelastic blade instabilities. First applications of IBC in order to achieve a higher lead-lag damping of the blade are presented in Ref. 19. These investigations are based on lead-lag displacement and rate feedback, see Fig. 23. The experimental investigation of this potential will be another important research topic at ECD.

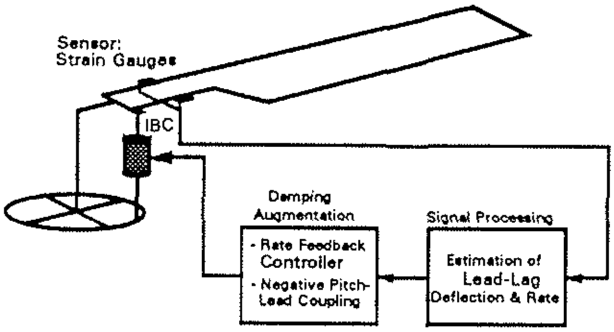


Fig. 23: Lead-Lag Damping Augmentation by Constant Gain Feedback

4 Penalties of Rotor Active Control Systems in Comparison with Alternative Systems

In 1994, ECD and ZFL conducted a joint study to compare different systems for helicopter vibration reduction, noise reduction and performance improvement. The study was based on a modern helicopter (gross weight 10 to - 13 to), comparing

- a passive rotor isolation system
- an active vibration reduction system
- rotor active control by HHC
- rotor active control by IBC.

System performance was assessed using results from wind tunnel and flight tests as described above. System weight and cost estimates were based on existing prototypes (vibration reduction systems) or pre-design studies (HHC, IBC). The active systems use servo-hydraulic actuators.

In order to achieve a fair comparison between the pure vibration reduction systems and the rotor active control systems, a hypothetical system design was considered which is especially tailored in order to fulfil the vibration reduction task. Besides this it turned out that such a design still preserves the full BVI noise reduction capability of IBC, since the control authorities and control loads needed for vibration and noise reduction are of the same order. Furthermore a limited power reduction capability still remains in case of IBC. One consequence of this design philosophy was the limitation of HHC and IBC operation to steady state flight conditions allowing to reduce the actuator force capacity by approximately 60%. Consequently the locking mechanism mentioned in chapter 2 is required in order to inactivate the rotor active control system in case of manoeuvre flight. Therefore separated actuators for primary and multi-cyclic control are used as indicated in Fig. 1. Based on the assumptions discussed above, the power and weight penalties of the rotor active control systems will be compared with those of the pure vibration reduction systems in the following sections.

4.1 Power and Weight Penalties

Besides the system weight itself, the fuel weight needed to satisfy the system's power consumption (fuel 1) and to carry the additional weight of the system (fuel 2) add to the helicopter weight. The data are based on a 2-hour flight which was the standard mission of the investigated 10 to helicopter. A power reduction of 4% at high speed (see Fig. 20) and a share of 50% of high speed flight in the typical mission were assumed.

The results of the study are gathered in the following three figures:

Fig. 24 compares the resulting weight penalties for the different systems. The passive vibration isolation system is used as a reference. The weight penalty for all systems is roughly 1% of the helicopter gross weight.

Although the IBC system has a weight penalty of about 18 % at the first view, the simultaneous power reduction capability of IBC is equivalent to 21 kg fuel weight reduction.

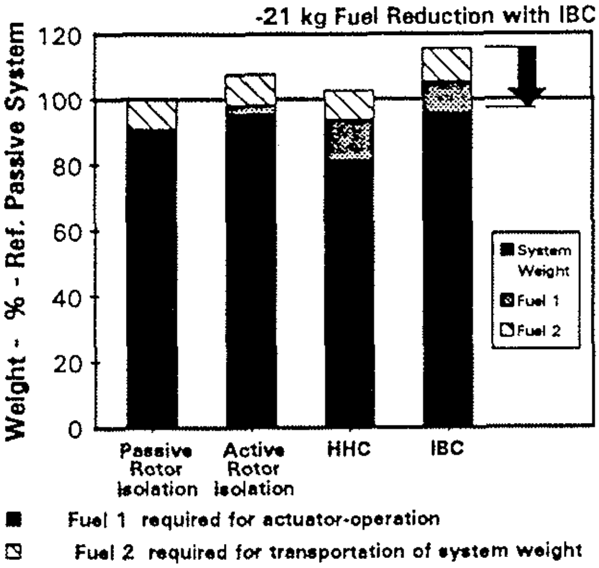


Fig. 24: Weight Penalties of Different Systems

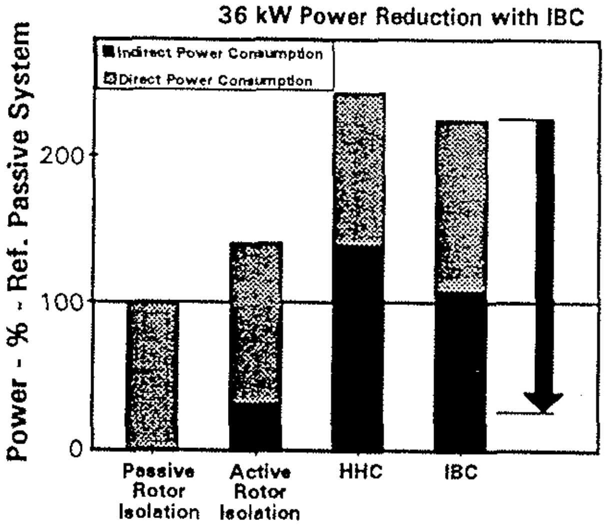


Fig. 25: Power Consumption of Different Systems

Fig. 25 shows the power consumption of the different systems. The power reduction due to 2/rev IBC is indicated by an arrow (36 kW).

Fig. 26 shows the weight share of different IBC components. Due to the moderate contribution of the actuator weights it may be concluded that efficient IBC systems designs are not restricted to 4-bladed rotors.

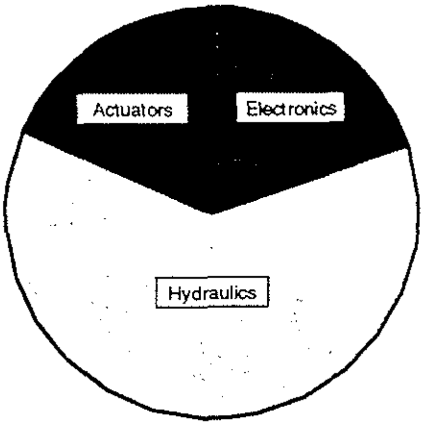


Fig. 26: Weight Composition of IBC System

4.2 Production and Maintenance Costs

An estimate of the costs is very difficult as long as there is no detailed design. Therefore this study concentrates to point out the major differences between HHC and IBC. IBC requires additional efforts for

- additional actuators (number of blades minus three)
- transfer of data and energy between non-rotating and rotating frame
- higher complexity of controller hard- and software.

Depending on the current experience with the flight tested IBC prototype of the Bo105, one can assume that the production costs for IBC are about 30% higher than for HHC. For the maintenance costs, the difference should be smaller.

For IBC as well as for HHC there are some requirements under economical aspects:

- Safety and airworthiness of the helicopter must not be affected by any failure of HHC/IBC.
- Most components have to be easily accessible and exchangeable.
- Parts that are not easily accessible (i.e. IBC mast fairlead) have to have the same TBO (inspection interval) as the related helicopter components.

Only under these circumstances operation of HHC/IBC systems is economically feasible.

5 Future IBC Actuation System Design Concepts

Additional IBC configurations which are currently investigated by several manufacturers and research institutions are summarised below.

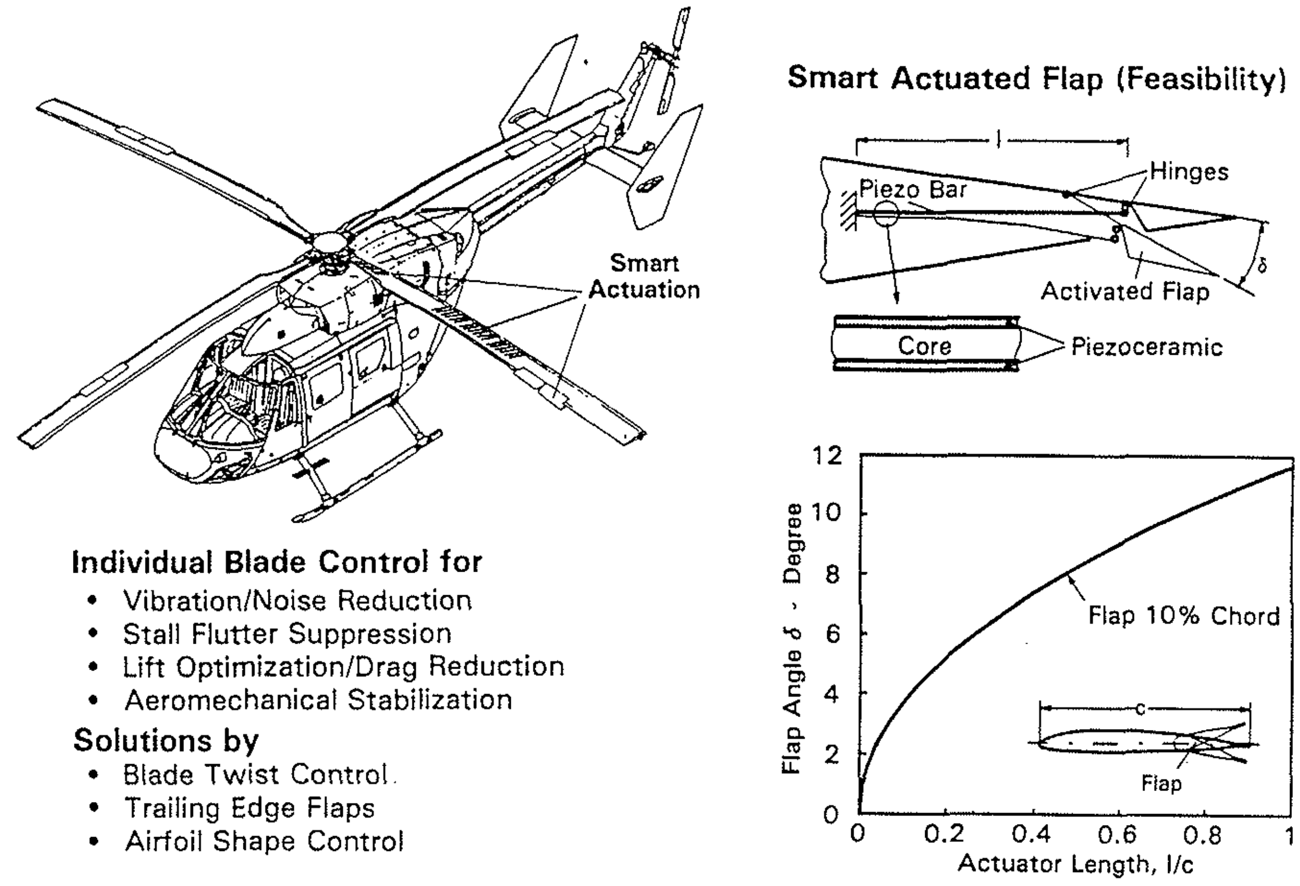


Fig. 27: Smart Materials in Future IBC Systems

Individual blade control is achieved here by the control of trailing edge flaps (Ref. 36, 37, 38), the blade twist (Ref. 39), or by changing the airfoil shape (Ref. 40). In the case of blade twist and trailing edge flap control, the blade angle-of-attack can be modified along the whole span of the blade. Consequently it should be possible to optimise the span wise lift distribution. In contrast to the conventional blade root actuation it will be possible to influence the angle-of-attack directly by avoiding problems caused by the blade torsional dynamics or by aeroelastic pitch-bending couplings. In the case of airfoil shape control the intention was to improve the stall behaviour by controlling the airfoil thickness.

The realisation of these new actuation systems was mainly based on application of smart materials, see Fig. 27, left.

Trailing Edge Flaps

Theoretical investigations (Ref. 41) and have shown that the trailing edge flap, (see Fig. 27, right) is a primary candidate for the realisation of a piezoelectric active rotor control system. The flap actuation can be realised by using active piezoelectric beam-elements in combination with a leverage arrangement which perform an appropriate kinematic amplification. The piezoelectric beam-element consists of two active plates bonded together. The required flap deflection is achieved by enforcing opposite strains in those plates. First results with a piezo-actuated flap on a model rotor (Ref. 42) showed promising results.

Blade Twist Control

Compared with the smart actuated trailing edge flaps, the potential of a blade with controllable twist is less promising. One reason for this is that shear deformations cannot be created directly by piezoelectric materials. Therefore the desired torsional deflections have to be enforced by appropriate blade designs which where investigated at ECD (Ref. 41). Another problem is related to the high torsion stiffness of the rotor blades. Consequently relative thick piezoelectric layers are required for the generation of any active shear stresses. Due to the additional stiffness introduced by these piecoelectric actuators, the torsional blade deflection is limited to very small values. Experimental results (Ref. 39) confirm these difficulties.

The main activities concerning new IBC actuation concepts at ECD are focused on the design of a piezoelectically actuated trailing edge flaps.

Airfoil Shape Control

Other concepts for extending the helicopter flight envelope influence the airfoil dynamic stall characteristics by using a leading edge slat, by blowing or by airfoil deformation. First experimental and analytical results performed at the DLR (Ref. 40) indicate that significant improvements of the moment and drag hysteresis are achievable by control of the airfoil thickness. This has been realized by an experimental pneumatic actuation system.

6 Conclusions

The following conclusions concerning the role of active rotor control in future rotorcraft can be drawn:

- Rotor active control technology is an efficient tool in order to cure a wide range of problems associated with rotor aerodynamics, aeroelasticity and aeroacoustics:
  - Cabin vibrations and BVI noise;
  - Compressibility effects and dynamic stall.

- IBC is the only rotor active control system which has the potential of
  - simultaneous vibration and noise reduction,
  - shaft power reduction (profile power red.),
  - flight envelope expansion (stall flutter suppression).

- Consequently it can be expected that IBC is the primary candidate for future rotor active control realisation.

- Prerequisites for efficient rotor active control applications in future helicopter projects are:
  - Reliable, effective and economical actuation systems. Smart materials are promising solutions.
  - Controllers which cope with unsteady flight conditions and which handle multiple tasks simultaneously. Time domain controllers are promising candidates.

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