Individual Blade Control by Servo-Flap and Blade Root Control
A Collaborative Research and Development Programme*

D. Schimke
Eurocopter Deutschland GmbH
München, Germany

P. Jänker
Daimler Benz AG
München, Germany

A. Blaas
ZF Luftfahrttechnik GmbH
Kassel, Gemany

R. Kube, G. Schewe
Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V.
Braunschweig/Göttingen, Germany

Ch. Keßler
Technische Universität Braunschweig
Braunschweig, Germany

Abstract

A collaborative programme is underway to explore the potential of the individual blade control (IBC) technology with regard to two aspects: Control laws will be developped and evaluated in flight using an existing blade root control system, and in a parallel activity, a smart actuation concept for a trailing edge flap will be developped and investigated in a wind tunnel test.

The development and evaluation of control laws will be performed with an IBC-System integrated in a BO105 helicopter, which was already used by ECD and ZFL for open loop higher harmonic control flight tests in 1990 and 1991. Compared to these tests, now also closed loop control laws will be evaluated and a more powerful experimental system will be installed: Increased control authority of the actuators, advanced sensors and measurement equipment and a fast and ruggedized computer for the IBC control laws. The expected results from this part of the programme are: Effective control laws for the reduction of cabin vibration and the external noise induced by blade vortex interaction (BVI) and the investigation of the potential of further control laws for rotor stabilization, stall delay, load and power reduction.

The activities within the second part of the programme comprise preliminary studies and simulations, the development of an integrated flap control unit on the basis of a piezoelectric actuation system, the integration into a full scale 2-D model of a rotor blade section and a 2-D wind tunnel test. Due to the more advanced level of IBC - technology of the used flap control unit, the objectives of these activities are quite different from the flight tests: Investigation of the servo-flap control vs direct lift control effect, the development and demonstration of a promising actuator technology with regard to control range, hinge moments etc. and the development of an integration concept for a full scale rotor blade.

The paper gives an overview about the programme, describes shortly the used facilities, discusses some design aspects concerning the flap control unit and will show theoretical simulations together with preliminary test results achieved up to now.

1. Description of the Programme

The rotor active control technology (RACT) programme, equally shared by the German Ministry of Research and Technology (BMBF) and by resources of the partners, formes the baseline of the activities described in this paper. The partners within the RACT-programme are EUROCOPTER DEUTSCHLAND (Project leader), the Deutsche Forschungsanstalt für Luft- und Raumfahrt, the Daimler Benz research establishment, the Technical University of Braunschweig and ZF - Luftfahrt.

---

* Presented at the 23rd European Rotorcraft Forum
in Dresden, Germany, September 16-18, 1997

The programme has two main objectives, which require quite different levels of technology for the test and evaluation:

- Inflight evaluation of individual blade control laws using an existing hydraulic blade root control system
- Wind tunnel demonstration of a servo flap control unit using a piezoelectric actuation system

Due to these different activities, the programme is divided in two quite independent parts:

- Control law development and flight tests
- Development of a flap control unit and wind tunnel tests

Even if these parts are independent from the today's point of view, the results of each part of the programme and the future activities will emphasize the complementary aspects: The control law design methodology used for the blade root control system will be applied to the flap control system in flight and the experiences with the piezoelectric actuation system could be used for the development of an advanced blade root control system.

Figure 1 shows the time schedules for the two parts of the RACT-programme and describes the milestones for the planned test activities.

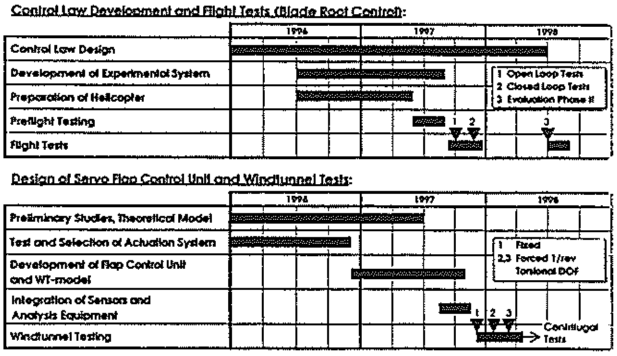

Figure 1: Time schedule

Because of the quite demanding test configurations in both programmes a considerable time is necessary for the development and preparation phase. Therefore the main test period will start after the completion of this paper. Nevertheless, some results will be shown from tests during the preparation phase.

2. Control Law Development

Within the flight test activities, open and closed loop control laws will be evaluated. The open loop control system will be used for 2 - 5/rev (14 - 35 Hz) inputs and is the same system used during the higher harmonic control flight tests in 1990/91. However, the increased control authority of 1.2 degree blade pitch angle is a decisive improvement compared to the former trials.

The development and evaluation of closed loop control laws is another important new element in these tests. It comprises designs for the reduction of cabin vibration and external noise, for rotor stabilization and the investigation of the potential of further control laws for stall delay, load and power reduction.

Figure 2 gives an overview about the open loop and two of the closed loop control laws evaluated in flight.

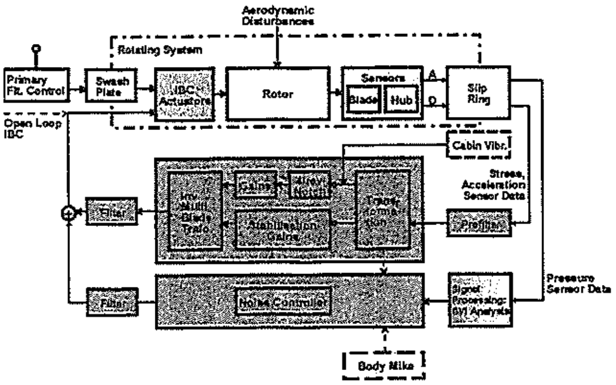

Figure 2: Open and closed loop control laws designed for inflight evaluation (Phase 1)

2.1. Reduction of Cabin Vibration

In order to increase the acceptance of helicopters by users and passengers the development of vibration reduction techniques is a main topic of current and future helicopter research. The importance of vibration comfort is expressed by guidelines like the ADS-27 defining an "Intrusion Index" as indicator for the comfort classification (Ref 1). This Intrusion Index is based on human sensitivity and should not exceed an upper bound of unity. Long-term objective is a "jet smooth ride" behaviour described by an acceleration level lower than 0.02 g. In comparison, the vibration level of today's conventional helicopters is located in the vicinity of 0.1g.

Regarding the available technology, it is assumed that this challenging objective will only be achieved by applying active systems for vibration reduction. Therefore, vibration reduction is emphasised as one of the key-points of the RACT programme. Two concepts for vibration reduction are taken into consideration, the control of hub loads - being focused on in this paper - and the control of airframe vibrations at selected locations.

Model: The evaluation of the dynamic properties of the BO105 serving as a demonstrator for the RACT programme is of great importance for an appropriate control law design. For this purpose, ECD applies the comprehensive rotor code CAMRAD II (Ref 2). The calculation of the dynamic properties consists of two parts in CAMRAD II. First, the helicopter model is trimmed to a given flight state. Then, a perturbation analysis of the trimmed state is performed in order to obtain a linear state space model described by a system of differential equations. Experimental data of open loop flight tests being part of the RACT programme are used for validation purpose.

For vibration control of the hub loads, the airframe is implemented as rigid body. The four-bladed rotor of the BO105 is modelled by non-linear finite beam elements. The resulting number of variables is reduced by modal techniques considering seven modes per blade. Regarding forward flight, a multiblade transformation - converting blade modes to rotor modes (collective, regressive cyclic, progressive cyclic, differential for a four-bladed rotor) - is performed in order to approximate the periodic environment of the rotor blades by a constant coefficient approach. In Figure 3, the eigenvalues of several rotor modes are presented as open loop poles (circles). The transformation from the rotating system to the non-rotating system is manifested by shifting the eigenfrequency (imaginary part) of the progressive and regressive modes by ±1/rev whereas the collective (drive-train dynamics suppressed) and differential forms are not affected.

Methodology for the Control Law Design: Frequency domain control as well as time domain control have been investigated by several researchers for IBC applications. For the RACT vibration reduction task, a time domain controller is preferred as its potential is believed to be higher concerning unsteady flight conditions requiring quick adaptations to sudden changes (Ref 3). Furthermore, time domain control based on high gains offers the possibility to adapt system dynamics favourably.

The vibration reduction task is solved by application of standard disturbance rejection control theory. This approach uses the "Internal Model Principle" (Ref 4, 5). It is based on appropriate servo-compensators in the feedback control loop of those output variables which should be unaffected by disturbances. The application of the "Internal Model Principle" requires a servo-compensator in the feedback loop being a model of the system which generates the external disturbances.

A typical design goal is to reject sinusoidal disturbances of the hub loads or the vibratory response of the airframe occurring at integer multiples of the blade passage frequency. Therefore, 4/rev oscillators have to be integrated in the controller dynamics leading to a closed loop transfer function with transmission zeros at the disturbance oscillation frequency. In Figure 3, corresponding transmissibilities for either vertical force and roll moment are demonstrated at the blade passage frequency 4/rev.

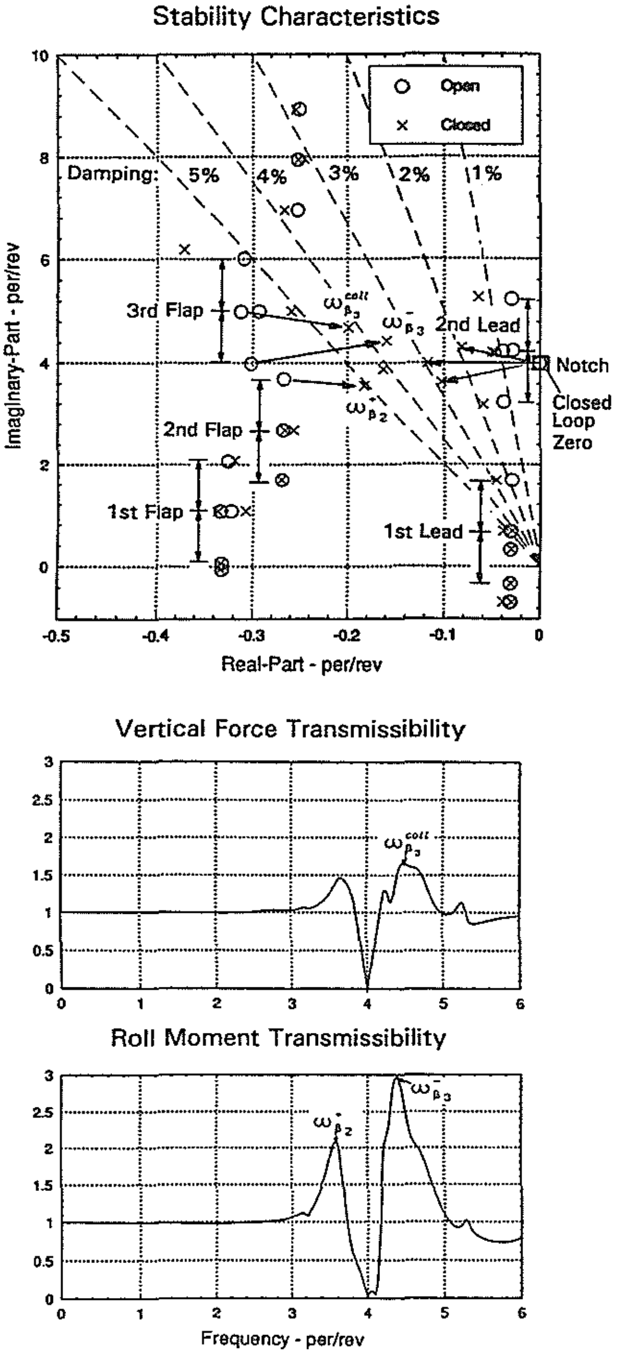

Figure 3: Analysis of 4/rev disturbance rejection controller (Open and closed loop) and transmissibility of vertical force and roll moment

Although the transmission zeros are obtained for very low feedback gains as well, high gains are preferred in order to improve the transient behaviour of the controller. The effect of high gains on the stability characteristics is shown in Figure 3. The closed loop poles of the compensator are shifted resulting in an increased damping of the controller dynamics. Furthermore, a benificial transmissibility characteristic is obtained with broad „notches".

The controller gains are calculated by an optimal output feedback approach (Ref 6) leading to a robust control design. Therefore, an appropriate state space model of the BO105 - obtained by CAMRAD II as mentioned above - was processed by the simulation software MATRIXx (Ref 7).

Results from Simulation: In Figure 4, the blade pitch angles and the controlled hub loads are shown as extracted results of a simulation run. This figure confirms the basic ideas of the controller design for vibration reduction within the RACT programme. The activation of the controller leads to diminishing controlled hub loads realised by transmission zeros of the closed loop system. Furthermore, this Figure demonstrates the ability of the selected controller to handle with transient conditions as the controller is switched on in an abrupt manner. The results are very encouraging as the disturbances decay significantly in about five rotor revolutions. The controller is expected to handle unsteady transient flight conditions in a similar manner. The IBC blade pitch angles for the four blades remain in an expected range and do not exceed hardware limitations given by the BO105 demonstrator.

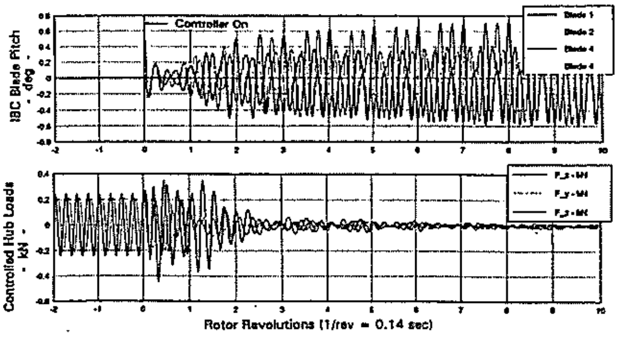

Figure 4: Suppression of 4/rev hub loads in forward flight

These results - showing an elimination of selected hub loads - represent one concept of the RACT programme in order to achieve the main objective of the vibration reduction task: improving the comfort for the occupants. Concerning the current control design, sensor data related to the main rotor are used for feedback control.

2.2. Ground and Air Resonance Stabilization

In addition to the control law structure shown in Figure 2, also a control law for the stabilization of ground and air resonance will be developed for tests in flight. This evaluation will take place in the second part of the flight test programme.

The background information concerning the problem ground and air resonance itsself and the published approaches to suppress it, will not be described within this paper, but literature to both topics can be found in Ref 8 - 15.

The validation of the rotor model and the development of the control laws is performed at the Technical University of Braunschweig in close collaboration with EUROCOPTER DEUTSCHLAND. The results achieved using the IBC-system are compared to a control law design in the fixed system. Whereas IBC needs a measuring equipment and actuators for each blade separately, the alternative approach makes use of the architecture of the classical stability augmentation system (SAS) integrated in the primary flight control system: The main difference to the SAS system are the higher gains needed for a faster stabilization of the rate response.

Model: The model used for this research work includes rotor-, body- and dynamic inflow states. The data set corresponds to a hingeless BO105 rotor. In order to show the effect of the control laws more effectively, the reference dataset assumes, compared to the series helicopter, a lower lead-lag damping level, achieved by a reduced structural lead-lag damping, a high landing gear (Ground resonance) and a low rotorspeed (Air resonance). A detailled description of the mathematical model used for these studies can be found in Ref 16.

Ground Resonance Stabilization: Figure 5 compares the open and closed loop eigenvalues in the complex plane for the ground resonance case. Four different controllers - two IBC and two SAS configurations - are compared. The two Individual Blade Controllers make use of the lead-lag states and additional flap states. All these signals can be measured directly using strain gauge signals. The SAS-approach uses pure roll, and pitch rate for the one controller, and in addition cyclic multiblade lead-lag states for the other controller. A description how to implement a simple p-q-controller in an existing flight control system can be found in Ref 17. The cyclic lead-lag states can be derived from rotor shaft shear-forces, or blade bending moment signals.

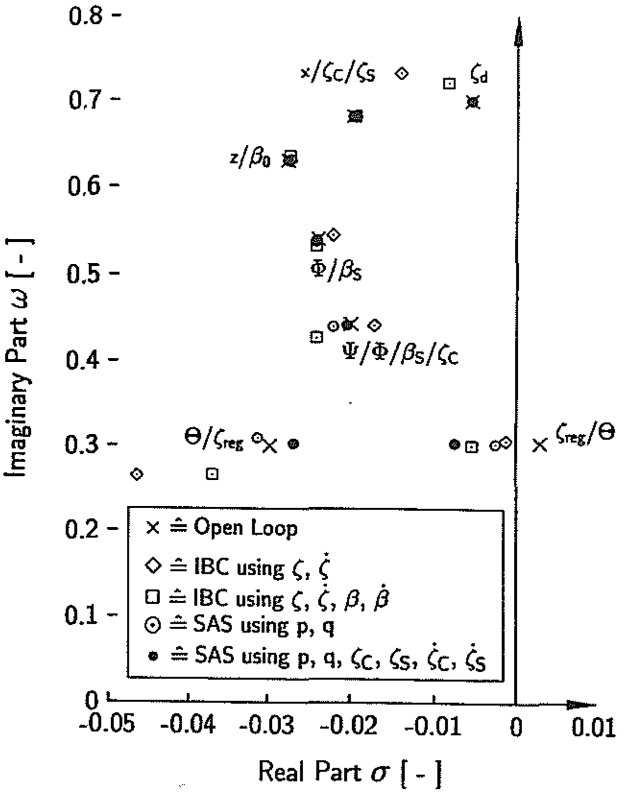

Figure 5: Helicopter on ground (50% thrust, 93% rotor speed), open and closed loop poles for different controllers

The open loop system (Figure 5) shows an unstable eigenvalue in the right part of the complex plane denoting a lead-lag pitch coupling. All four controllers stabilize this unstable eigenmode. The SAS-controllers do not affect most of the eigenvalues, since the feedback gains remain small. Of course, the more states are fed back, the better the obtained damping. The results obtained with the simple p-q-controller agree with those from Ref 17. Compared to SAS, IBC shows less closed loop system damping. Again, the more states are fed back, the better the results. The flap eigenvalues are shifted towards higher damping levels without changing the eigen frequency significantly. This may be a direct consequence of the coupling between flapping and lagging motion. Since the SAS-approaches show higher closed loop system damping than IBC affecting only the important rotor-body modes, the SAS is in this case advantageous compared to IBC.

Air Resonance Stabilization: Figure 6 shows the open and closed loop regressing lead-lag damping plotted vs. the advance ratio.

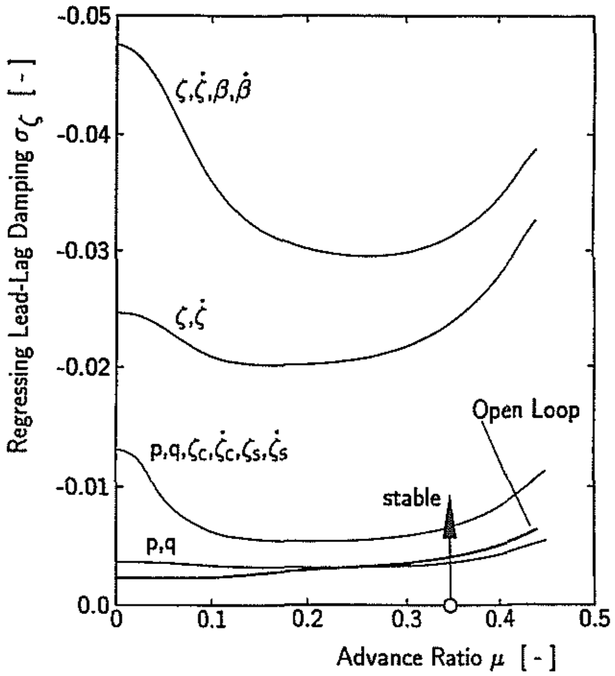

Figure 6: Lead-lag regressing damping vs advance ratio for different controllers

Applying both individual blade controllers optimized for the hovering helicopter it can be seen, that a sufficient damping level can be obtained for all advance ratios. Of course, the enormous damping margin for the design point can not be maintained in forward flight, but the results are very promising. In contrary to the ground resonance investigation, the SAS-controllers show lower closed loop damping values. For the simple p-q-controller, the closed loop case has much less damping capacity than the IBC-design and beyond an advance ratio of 0.23 a lower damping than the open loop system. Of course, these results show only a first tendency without an optimization of the high speed regime.

2.3. Reduction of the External Noise

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. Figure 7 shows the typical flight condition for BVI (Ref 18), where a BVI noise reduction is effective.

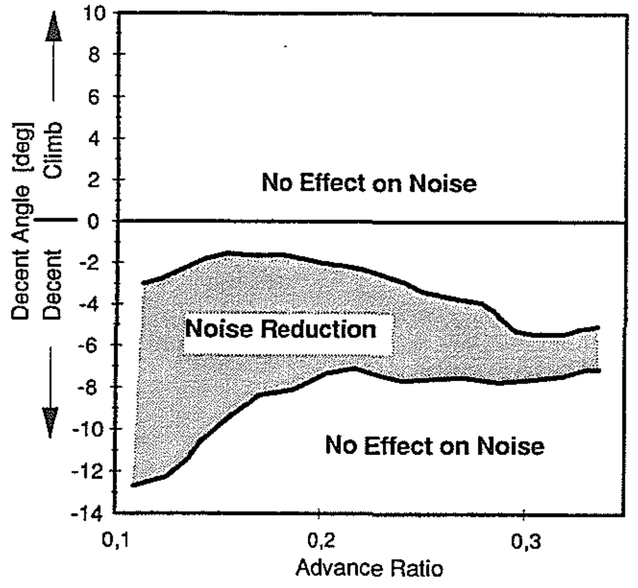

Figure 7: Typical flight conditions for blade vortex interaction (BVI), Ref 18

There are three different effects which may explain the efficiency of higher harmonic control inputs to BVI noise:

- Reduction of the blade pitch angle at the position where blade vortex collision appears.
- Reduction of the vortex strength at the position where the tip vortex is generated.
- Increase of the miss-distance between vortex and blade.

In wind tunnel experiments, the concept of higher harmonic control in both, fixed (HHC) or rotating system (IBC) has been proved to be very effective for BVI noise reduction. Noise reductions up to 8 dB were measured by single frequency inputs (2 and 3/rev sinus functions). However, the resulting noise reduction is highly dependent on the phase and amplitude of the higher harmonic blade pitch input. Figure 8 summarises the noise results of the baseline case without HHC and the optimum higher harmonic input phase versus the descent flight path (advance ratio 0.15). As long as BVI noise is generated, noise reductions up to 6 dB can be achieved. However, if the input phase is not adjusted to the flight condition, a smaller noise reduction or even an increase of BVI-noise can be induced.

Several tests with flight condition variation (Ref 18, 19, 20) indicate the need for a closed loop control system which is able to control the phase with respect to the BVI noise generation region. A promising concept for a BVI noise control is 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 used dynamic pressure sensors on the rotor blade together with the BVI - analysis is promising, but for product application other sensors and different analysis methods will be also tested.

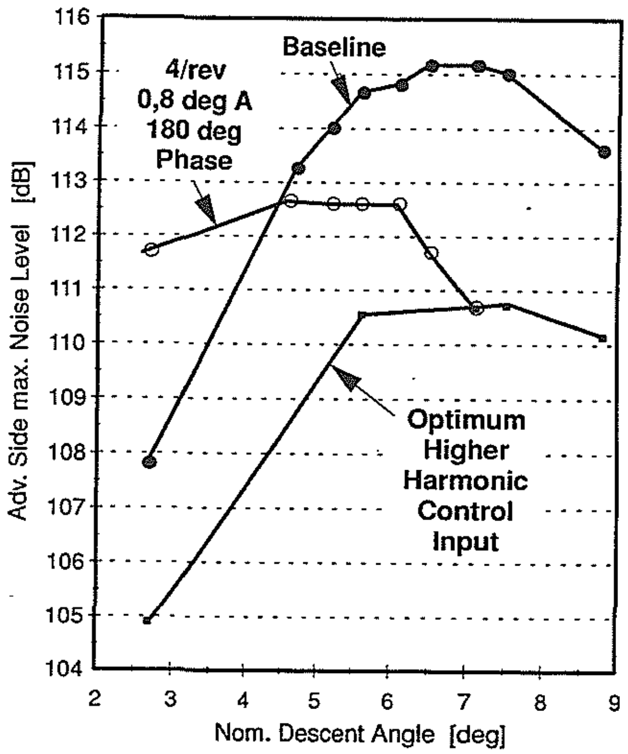

Figure 8: BVI noise reduction vs. descent glide path angle (Ref 19)

Experiences with Open Loop Control Laws: An important result of the full scale IBC tests (Ref 20, 21) was the correlation of the optimum input phase for high BVI noise reduction with the azimuth region where the blade vortex interactions occur. The principle can be seen in Figure 9 for a simulated 6 deg approach flight condition (advance ratio 0.15) with a 2/rev and 3/rev IBC-input. The measurement was done with one fixed microphone positioned inside the BVI noise radiation zone. A noise reduction is obtained if the blade pitch is reduced at the azimuth position where the tip vortex interacts with the following blade, which is accompanied for 2 and 3/rev input modes by an increase of the pitch in the section between vortex generation and collision. Depending on the vertical position of the vortex relative to the blade, the pitch angle has to be either increased or decreased. In addition, BVI noise is also reduced if the blade pitch is reduced at the azimuth angle where the corresponding tip vortex is generated.

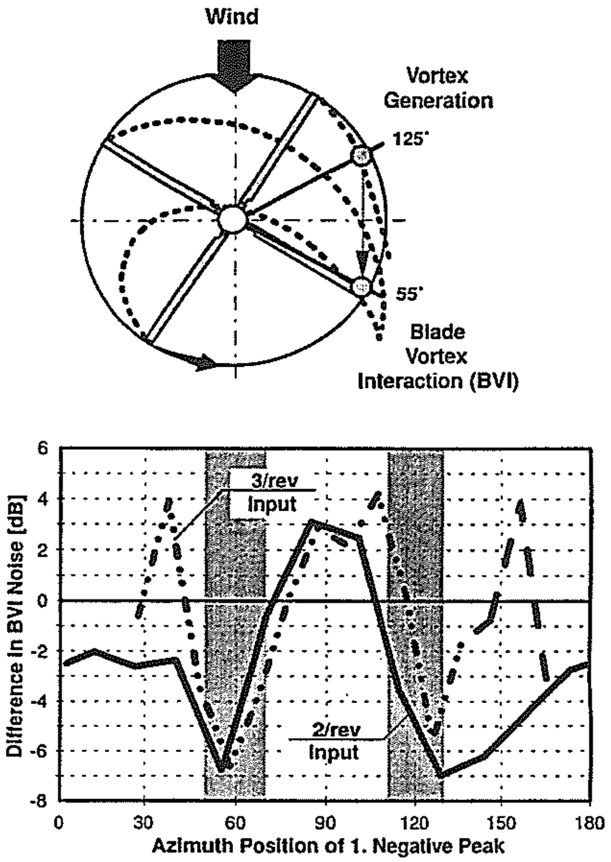

Figure 9: Variation in noise level for a 2/rev and 3/rev input function (fixed microphone position on advancing blade side, 6 deg descent glide path, $\mu = 0.15$)

Measurements of higher harmonic inputs indicated, that noise reduction is related to a vibration increase and vice versa. The potential of rotor active control with respect to simultaneous noise and vibration reduction was investigated in the NASA Ames IBC wind tunnel tests by multiharmonic inputs (Ref 20, 21). The concept consists of a 2/rev input mode for noise reduction, as this input mode is not transmitted from the rotating to the non-rotating system. The other harmonics (3, 4 and 5/rev) were used for vibration reduction. It could be shown that even very small amplitudes of IBC input resulted in a significant reduction in of the vibration level in parallel to the noise reduction provided by the 2/rev input.

BVI Analysis: While feedback signals for an IBC vibration controller can directly be derived from a sensor signal(e.g. accelerometers), no comparable sensors are available for a BVI noise controller. A microphone being attached outside the fuselage could be used in principle, however, it will remain outside the main BVI radiation zone.

Another quite promising approach derives the actual BVI noise level from pressure transducers at the rotor blades. The output signals of these transducers allow a BVI noise identification with respect to a quantification and location of the blade vortex interaction, provided they are preprocessed properly either in time or in frequency domain.

Figure 10 and 11 show an example for a BVI-analysis using the wavelet transformation proposed by the Daimler-Benz research centre. Tests with data from Ref 22 show, that this new method for data analysis could be used for a reproduceable identification of the quantity and the location of the interaction.

Two further methods were developed by DLR and are already integrated and tested on a fast preprocessing computer for the real time application in flight.

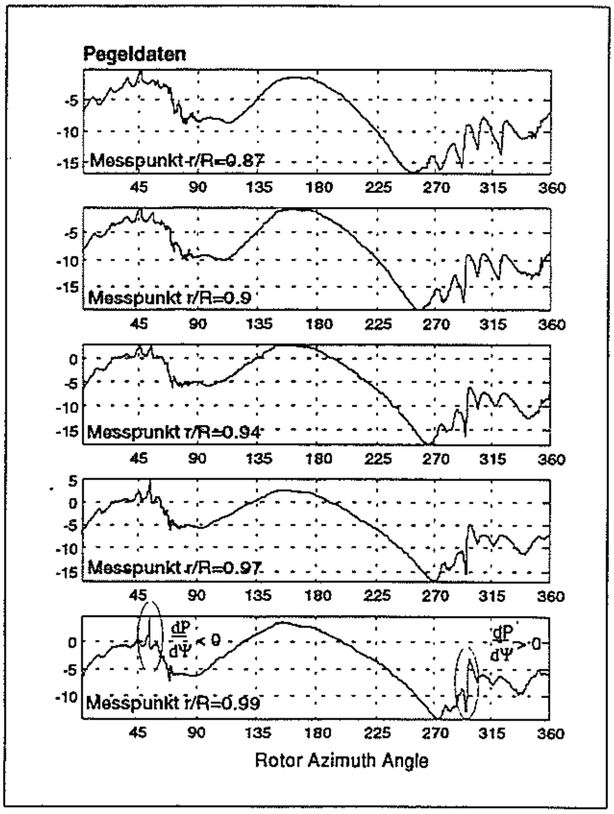

Figure 10: Pressure data from Ref 22

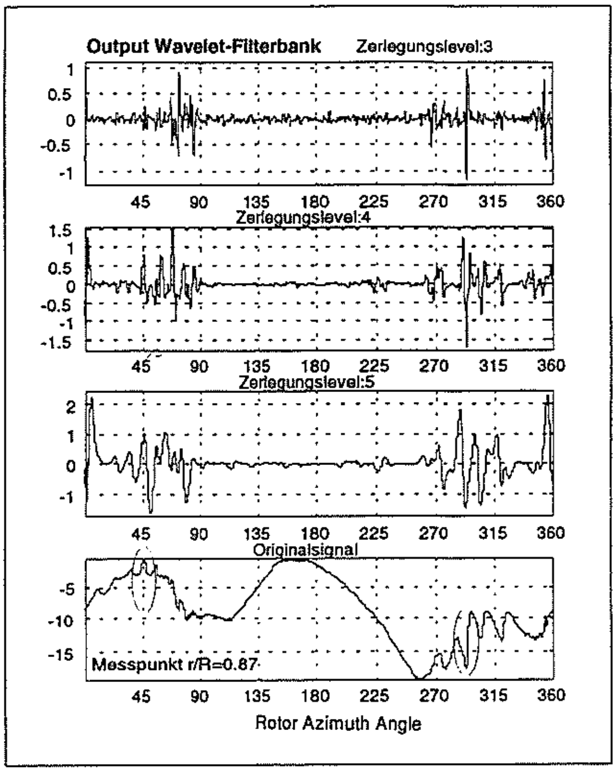

Figure 11: Identified BVI-locations by wavelet transformation

Concepts for Closed Loop Controllers: Several concepts are defined for the realization of a closed loop controller. In a first step, all controllers will use the 2/rev rotor harmonic, but will differ in the used sensor signal, the way of preprocessing (BVI-Analysis) and in the control law architecture: Starting with the database from the open loop trials, simple feedforward control systems combined with flight state informations will be tested as well as feedback controllers. Because of the different effects which may explain the efficiency of higher harmonic control inputs for the BVI noise (compare Chapter 2.3), it is important to concentrate not only on one method, but to test several controllers together with the sensor information and the preprocessing needed.

One of the more complex approaches will be developed at DLR and uses an additional identification: This method takes into account, that the output signals of the pressure transducers will vary from one revolution to another due to flight control and atmospheric disturbances, which may lead to strong fluctuations of the estimated noise level, independent of the online BVI analysis algorithm used. Therefore, this control algorithm tries to minimize the rotor noise emissions before increasing again due to disturbances. Although the strong initial control activities will be limited artificially in order to avoid overloads in the rotor control system, a closed loop system behaviour can be expected which makes it possible to keep the BVI noise emission minimum, even in case of varying flight conditions. To account for the corresponding changes of the rotor reaction to IBC inputs, the controller will be combined with an online identification algorithm which makes it possible to keep the feedback gain adjusted in an optimum way.

3. IBC-Demonstrator and Flight Tests Planned

The analysis of the potential of IBC and the evaluation of the control laws in flight are decisive objectives of this part of the programme. Therefore, an important step for this objective was the preparation of the helicopter BO105 S1, the extension of the existing IBC system to a higher control authority and the development of an experimental system with very high requirements especially in terms of computation time, data rates and sensors. The result of this work is a cost-effective IBC-demonstrator, which is described in the following.

3.1. The Individual Blade Control System

Since 1986, ZF Luftfahrttechnik (ZFL) has designed, developed and tested an Individual Blade Control (IBC) System for helicopters. Its key component is a servo-hydraulic actuator, that replaces the conventional rotating pitch links in the helicopter main rotor. Whereas actuators in the fixed frame can only control certain harmonics of the rotor frequency, the IBC actuators in the rotating frame allow individual blade control, only limited by the capability of the actuators. Additional components of the ZFL-IBC-System include hydraulic and electric sliprings, hydraulic components, and a digital controller. Safety of flight is obtained by an emergency shutdown feature, that locks the actuators mechanically if hydraulic pressure drops. The IBC hydraulic system is separated from the helicopter hydraulics and can be shut down manually or automatically. A detailed description of the ZFL-IBC-System is found in Ref 23.

The ZFL-IBC-System was flight tested first in 1990 and 1991 (Ref 24). Although the system was designed for a usable IBC pitch angle of 1.2°, it was limited mechanically to ± 0.42° due to safety motives. In 1993 and 1994, a more powerful variant of the system was tested on a full-scale BO105 rotor in the 40x80 ft Wind Tunnel at the NASA-Ames Research Center. It was capable of ± 3.0° IBC pitch angle and was tested with tunnel speeds up to 190 knots (Ref 21).

The results of both flight and wind tunnel tests were encouraging, and in the upcoming flight tests, the full capability of the flight test system of ± 1.2° will be used. One major intention of this flight test campaign is to verify the BVI noise reductions of about 6 dB that were measured in the wind tunnel (Ref 25).

3.2. The Experimental System

Figure 12: The IBC-demonstrator BO105 S1

Figure 12 shows the helicopter BO105 S1 in flight. In addition to the IBC system, an advanced experimental system is integrated in the helicopter:

- Rotor measurement equipment: More than 50 sensors are used in the actuation system and on the rotor (strain gauges, acceleration sensors, pressure transducers).
- Interface Computer: A very fast computer system was developed for digital data recording, a preprocessing of sensor signals (BVI-analysis), the transmission of data to the control computer, to telemetry and other systems. For the recording of the pressure data and the fast transmission of data to the control computer, a sampling frequency of about 3500 Hz (synchronized with the rotor speed) will be used.
- Control Computer: A ruggedized multipurpose computer is installed for the calculation of the different digital controllers. One of the main requirements is a maximum time delay of less than 4 ms from the sensor to the output of control computer. The sampling frequency is also synchronized with the rotorspeed and is about 500 Hz. The connection to the interface computer is realized by a transputer link.
- Telemetry: The telemetry provides the observation of safety critical signals, the control activity and the flight states. In addition the telemetry is important during the optimization of the control law gains.
- GPS-system: Installed for a precise recording of the flight path.
- Noise measurement on bord: for the correlation of ground and helicopter noise (Theory vs measurement) and for use in the noise controller

3.3. Flight Tests with Open Loop Control Laws

Noise measurements will be made by use of a large ground instrumentation. As shown in Figure 13, 11 microphones will be arranged in a line perpendicular to the flight path covering a range of ± 300 m. The microphones will be mounted in an inverted position over a metallic plate to minimise reflection influences. More microphones will be concentrated on the advancing blade side, where the microphones are positioned similar to the microphone arrangement from previous wind tunnel tests with respect to the noise propagation directivity. As the noise, generated by BVI, is strongly dependent on the helicopter flight conditions, the flight path (glide path angle and speed) will be monitored by a Differential GPS equipment. The test matrix consists of a series of different approach conditions followed by a fly-over and a take-off condition. The IBC inputs will be defined with respect to phase and amplitude on the basis of the wind tunnel test results. The noise testing should give a proof of the efficiency of IBC on the noise emission of a helicopter and will form the necessary data base for the design of the noise control law.

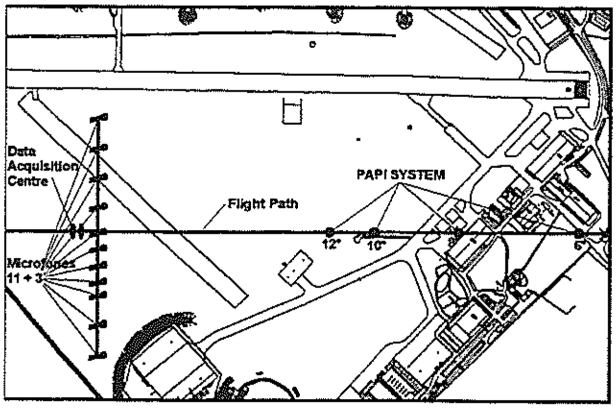

Figure 13: Arrangement of the open loop flight tests

3.4. Further Flight Test Activities

According to the control law design described in Chapter 2, an inflight evaluation will be performed after the open loop flight tests. The tests of the control laws are divided in two flight phases. During the first phase, the centre of gravity is the evaluation of the vibration and noise controller.

For the reduction of cabin vibration, in a first step, the optimization of the gains derived from the controller design and simulation have to be adapted. In a second step, several configurations of the controller will be tested, in order to select the most effective one.

As already mentioned in Chapter 2.3.3., an important aspect for the noise controller is, that different approaches with regard to the level of complexity and the used (preprocessed) sensor information will be tested. Experiences and results gathered from several wind tunnel tests, will define the baseline of the planned tests. Therefore, a first important experience will be, to what extent the existing results can be transferred to the flight test condition.

In the second phase, the ground and air resonance stabilisation together with the exploration of the further potential of IBC with regard to the reduction of the power required and the delay of stall phenomena will be tested. The center of gravity of these investigations will be defined after the Phase 1 trials.

4. Development of an Integrated Flap Control Unit

The main objective for this development was to create an advanced full scale solution, which could be integrated in a rotor blade in a second step. For this first step, important design aspects for the rotor blade (e.g. centre of gravity, mass) were already taken into account, in order to be prepared for the integration of the flap control unit in the rotor design. In the following this development process from the aerodynamic layout to the design of the flap control unit and the integration into the wind tunnel model is described.

4.1. Layout of the Servo-Flap

To simulate the quasi-steady behaviour of a rotor blade with a part-span trailing edge flap, a simple model was established based on Ref 26. The model considers compressibility effects and takes into account some corrections based on experimental results. The complete model includes the following effects on the rotor blade:

- direct lift due to flap deflection
- pitching moment due to the flap deflection
- elastic twist of the blade due to the pitching moment
- lift due to the elastic twist respectively the lift due the servo effect

The trim condition is taken from a flight mechanic model for a typical cruise flight condition of the EC135. The geometrical data of rotor blade are as follows:

Radius:	5.1 m
Chord:	0.3 m
Flap length/Position:	0.5 m/0.8-0.9 R
Relativ flap chord:	15 % (varied)

An important result of the studies was, that at low angles of attack and high Mach numbers (advancing blade) the elastic twist dominates the blade lift, whereas at high lift coefficients and low Mach numbers the direct lift due to the flap deflection overwhelms, but the absolute value of the achieveable lift is very small at the retreating side. Figure 14 shows the behaviour of the two parts of the lift vs azimuth angle for a cruise flight condition. The aerodynamic requirement for this calculation was an additional lift due to flap deflection of 1000 N. The figure shows, that the direction of the resultant lift due to flap deflection changes the sign at the azimuth positions 225 and 315 degree. At this position there is no change of the lift by flap deflection possible. Looking to the technical use of lift, only the lift due to twist at the advancing side is of technical importance. For the 15 % (plotted in Figure 14) and 20 % flap more than 20 degree are necessary for the required lift.

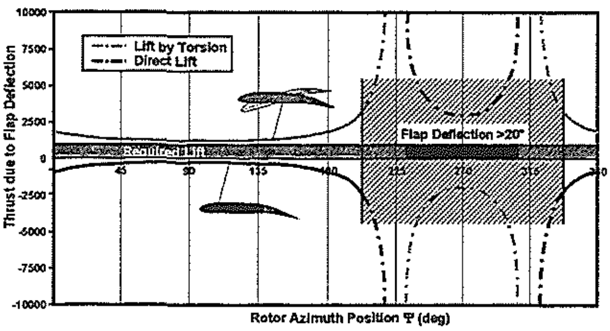

Figure 14: Different contributions to the lift due to flap deflection vs azimuth

However, the use of the direct lift effect may be possible for a different design of the rotor blade and the flap. High torsional stiffness and an enlarged flap may lead to an usage of the direct lift effect: On the advancing side the high stiffness and on the retreating side a chordwise and spanwise enlarged flap leads to this different design approach. Investigations and tests for this design will be performed by ONERA in collaboration with EUROCOPTER France.

Because the realization of the actuation unit by an advanced system was an important objective of this programme, a further requirement came from the limited achieveable hinge moment of the actuator, which has to control the flap at all the calculated trim conditions of the rotor blade. This requirement together with the described calculation led to the concentration on the the servo-flap effect.

For the detailled specification of the required hinge moments, a more complex aerodynamic code was used including the boundary layer (Ref 27). Figure 15 shows the requirements derived from these calculations in comparison with the performance graph of the actuators. The baseline for this calculation was the aerodynamic condition representing the 0/180, 90 and 270 degree azimuth position and a required lift vs azimuth, derived from simulations using a control law for the reduction of the cabin vibration. The diagram shows, that the 0/180 degree position requires the highest hinge moment, because of the combination of the hinge moment due to the angle of attack and the required flap deflection. From the figure, it can be derived that within the designed flap range of ± 10 degrees not all flap deflections can be reached. An improved design approach for the actuation system is on the way to fulfil the full flap range also for the 0/180 degree (Ma=0,54) trim position. The dotted line indicates the aerodynamic requirement at Ma=0.33, but, as shown in Figure 14, the required flap deflection is quite high and the used effect results not from the lift due to torsion, but from the direct lift effect (Change of sign of the control gain vs azimuth).

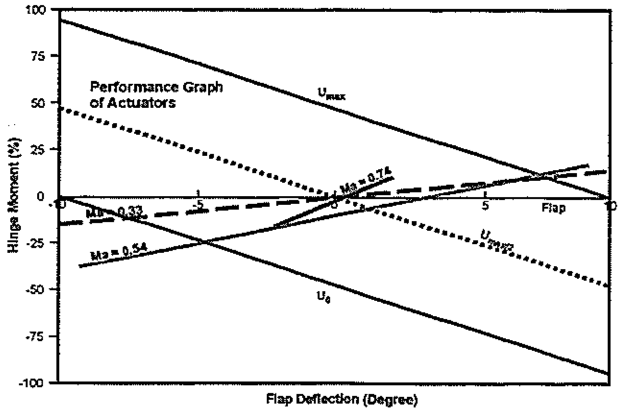

Figure 15: Aerodynamic hinge moments and performance graph of the actuation system.

4.2. Design of the Piezoelectric Flap Control Unit

The application of piezoelectric actuators focuses basically on micropositioning like applications in printer technology. Over the past few years, interest in piezoelectric actuators has increased greatly. The advantages inherent in piezoactuators compared to conventional actuators are numerous: Compact design, high speed, high precision and optionally controllable stroke travel. Research into „smart materials" and adaptive structures at Daimler Benz aims to develop actuators for macropositioning, in order to permit utilizing solid state actuators for advanced mechanical applications. For the longterm objective to realize the adaptive rotor blade by „smart" solutions, the integrated trailing-edge flap is a promising technical approach, which is expected to be used in flight in the near future.

This applicatioin is a very challenging task for the actuator technology. The most important considerations for the implementation of the actuator into the rotor blade are: Little space, high dynamic response, large stroke and high force capability and the high centrifugal forces together with accelerations in the flap and lag direction. During the planned 2-D wind tunnel trials most of these aspects will be regarded. The demonstration of the acceleration forces will be performed in a special test after the wind tunnel trials.

Today, only solid state actuators are regarded to be suitable for this task. A study performed at Daimler-Benz comparing the properties of today available actuator materials proofs piezo ceramics to be superior. A suitable compact and lightweight, high-performance actuator system with a stroke of 1 mm and a blocking force of 2000 N has been created by the Daimler-Benz Research and Technology sector. The actuation system is a hybrid system comprising a d_{33} stack and a stroke amplifier, and is characterized by good dynamic properties. The resonance frequency amounts to 700 Hz.

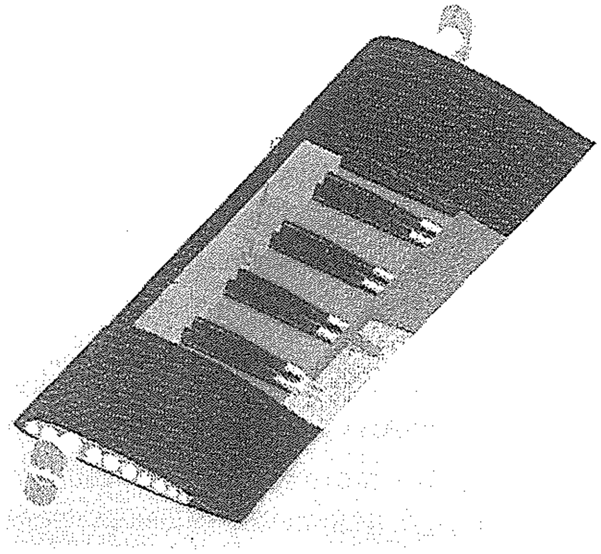

Figure 16: Design concept of the integrated flap control unit

Figure 16 shows the design concept of the actuation system integrated in the wind tunnel model. It consists of four piezoelectric actuators consisting of a stacked piezo bar and a mechanical amplification. Two actuators each control one of the two flaps (0.25m span each). This duplex arrangement normally works like one flap of 0.5 m, but can also be used in single mode (e.g. in case of failure of one system).

5. Windtunnel Tests

5.1. The Transsonic Wind Tunnel

The wind tunnel tests will be conducted in the transonic wind tunnel of DLR in Göttingen. The recently modified wind tunnel is a continuous, single return facility with three exchangeable square test-sections (size: 1 x 1 m^2) for the subsonic, transonic and supersonic speed regime. The absolute size of the test section is ideally suited for 2-D wing experiments because on the one hand it is large enough to permit the use of models equipped with sophisticated measurement techniques (pressure transducers etc.), on the other hand it is small enough to keep the effort concerning the structural dynamic properties of the test set-up and adjustments of the mounting system in reasonable limits. The same is valid for the application of advanced optical measuring techniques such as pressure sensitive paints (PSP) or particle image velocimetry (PIV). The measurements will be performed in the transonic test section with perforated walls. Alternatively a test section with adaptive walls is available. Especially for our planned measurements the Ma-number range will be extented down to Ma = 0.3.

The first measuring campagne with the new test setup was performed in May this year. The main objective was the measurement of steady and unsteady pressure distributions and forces using an oscillating supercritical wing. Although the airfoil of the wind tunnel model for this test campagne was different to the model used with the integrated flap control unit, these trials were important, in order to test the feasibility of the forced oscillation and the measurement equipment. Thereby the risk for the tests using the model with the piezoelectric flap control unit could be reduced.

5.2. Test Set-Up for Forced Pitch Oscillations

A schematic sketch of the test set-up and a view of the whole test section is presented in Figure 17 and 18.

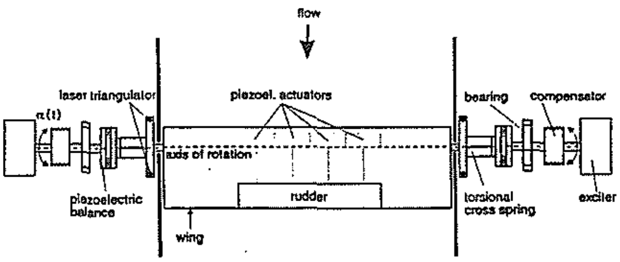

Figure 17: Test set-up for forced pitch oscillations

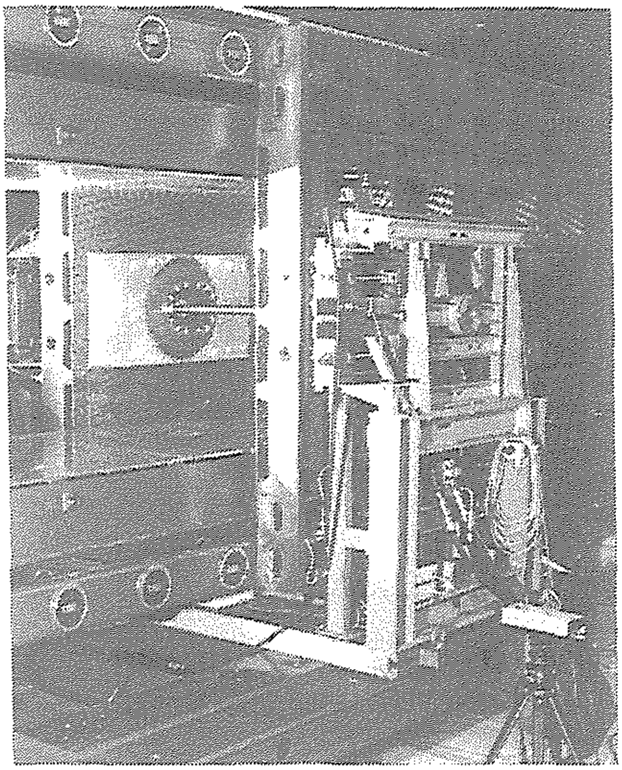

Figure 18: View of the whole test section

The 2-dimensional wing model with a chord length of 0.3 m, a span of 1 m and an OA312 airfoil is manufactured of carbon fibre (design concept see Figure 16). It is attached on both ends to a pitching spring and a both sided torsional excitation, providing a fully symmetrical set-up. Both hydraulic exciters have to work with a phase shift of 180°, which is performed by a special controlling system, which was tested during the trials mentioned above. Between the outer torsional exciters and the inner cross spring (pitch) a piezoelectric balance is mounted in order to measure steady and unsteady forces. On each side the balance consists of four multi-component force transducers. The main feature of such wind tunnel balances is their high stiffness. Thus piezoelectric balances are in particular suitable for dynamic measurements (Ref 29, 30). In addition the pressure distribution is measured for one cross section, especially for the analysis and the validation of the dynamic measurements.

Four laser triangulators determine the pitching angle $\alpha(t)$ of the wing itself. This angle is different from the adjusted angle at the torsional exciters, if the torsional spring is installed. A bar, positioned between the wing model and the balance, provides a reference plane for the optical measurement of the time-dependent position at each side of the wing. This is necessary for detecting differences in the bothsided excitation. In case of exceeding a specific threshold the hydraulic system jumps to a predefined state.

The rigid-body pitching frequency is determined by exchangeable cross springs, which can be blocked. Additional masses allow an effective variation of the moment of inertia and the center of gravity, in order to tune the torsional degree of freedom.

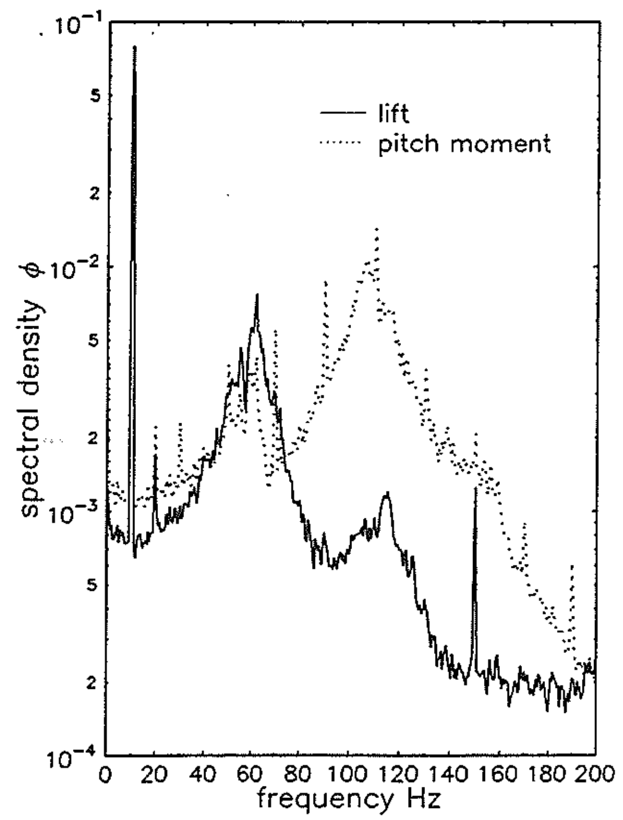

Figure 19: Power spectra of the unsteady lift and moment of an oscillating wing (f = 10 Hz, $\alpha_0 = 1°$, $\alpha_{-} = \pm 0.6°$, Ma = 0.7)

Figure 19 shows a power spectrum of the unsteady lift and moment of an oscillating wing taken at Ma = 0.7. The cross-springs were dismounted. The peak at 62.5 Hz in both spectra is caused by the heave motion and the peak at 107.5 Hz by the torsional motion of the wing. These frequencies are determined by the suspension in the test setup.

Summarizing the test campaign the measurements showed the following results:

- The bothsided torsional excitation including the fail-safe devices work very well
- The twinned piezo-balance delivers reasonable steady and unsteady results, although there is no common base for the balance

The lowest heave frequency of the wing suspended in the test setup is highly dependend on angle of attack and aerodynamic load. This frequency must be increased, because it lies in the range of the desired forced oscillation of the flap control unit (0 - 42 Hz). This point will be improved by modifying the bearings in the excitation part of the test setup.

5.3. Windtunnel Tests and Expected Results

Three configurations will be tested within the test period. In the first configuration the wind tunnel model is fixed and the static and dynamic forces and moments are measured. Beside static measurements, the only excitation will be the flap deflection. The type of input will be the rotor harmonics from 2 to 5/rev. The expected results from these tests will be:

- Reliability of actuation system
- Achieveable hinge moments
- Test of measurement equipment of wind tunnel model and of wind tunnel test section

In a second configuration selected dynamic measurements will be performed and compared with the results of the first configuration. For this test the whole model will oscillate with 1/rev (7 Hz) and the flap deflections will be varied like for the first configuration. The objectives of these tests are:

- Comparison of dynamic and static measurement
- Validation of Navier-Stokes code using the measured pressure distribution

In a third configuration a torsional degree of freedom is included, simulating the torsional motion of the rotor blade in terms of torsional stiffness and frequency. By this test, the effect of the servo-effect will be tested. The expected results are:

- Achieveable lift for different flap inputs (e.g. 2-5/rev) and several trim conditions
- Transfer characteristic of servo-control principle

5.4. Use of Results and Planned Further Activities

The activities planned after the wind tunnel tests can be divided in two steps: The first one is already in preparation and will start immediately after the wind tunnel tests. It is partly already included in the RACT-programme, partly a follow-on activity sponsored by the Daimler-Benz research centre.

These activities comprise the optimization of the flap control unit according to the experiences from the wind tunnel test, a preparation of the actuation system for a centrifugal test, the integration of the actuation system in a real rotor blade segment, the development of an energy and data transmission system and centrifugal force and acceleration tests.

After a successful demonstration, that the flap control unit is able to control the flap in the rotor environment with regard to aerodynamics and acceleration forces, the technology is mature to be tested on whirl tower and in flight.

6. Conclusion and Future Perspective

Beside the planning for the follow-on activities with the flap control concept including tests in the wind tunnel, on whirl tower and in flight, research activities at the DB research center, the DLR, the ONERA and the Universities are underway to explore the potential of individual blade control with respect to mid- and longterm aspects. However, from industry point of view, the potential for the product improvement and the maturity for the product application are the important criterions for an engagement on this domain. Because the actuator technology is not yet ready for a direct product application, the assessment of the potential for the product improvement is decisive. In order to estimate this potential, the following questions have to be answered:

- How much benefit for the helicopter can be expected by controlling the individual blade with the existing technology?
- Which new integrated actuation system or smart material can be realized on a full scale rotor?
- How much additional benefit and which new potential is provided by the new actuation sytem or smart material?

The evaluation of an IBC-system using a blade root control system in flight will try to answer the first question. The discussion of this question is not new, however, the high control authority, the fast computation system and advanced sensor equipment together with sophisticated control laws will enable this IBC-demonstrator to demonstrate the full potential of this control concept in flight. In addition, the experience in the control law design methodology will be used for similar systems, e.g. for the servo-flap.

Before answering the second question, it has to be stated, that, in spite of the amount of publications about the potential of smart materials for the application to the helicopter, the usage of this technology on a full scale rotor in flight is not yet realized. Because for the industry the full scale application is much more interesting than the advanced smart solution on a model, the logical first step for Eurocopter was the realization of a servo-flap useable on a full scale rotor. The performance of the piezoelectric actuation system, developed by the Daimler-Benz research centre, is expected to fulfil the requirements of this objective.

The third question comprises the future development on the domain of smart materials and actuation technology together with a possible new potential derived from this technology. Figure 20 shows the IBC-systems, discussed in this paper and possible future systems. In addition, the two contour plots give an overview about the aerodynamic condition of a helicopter at high forward speed.

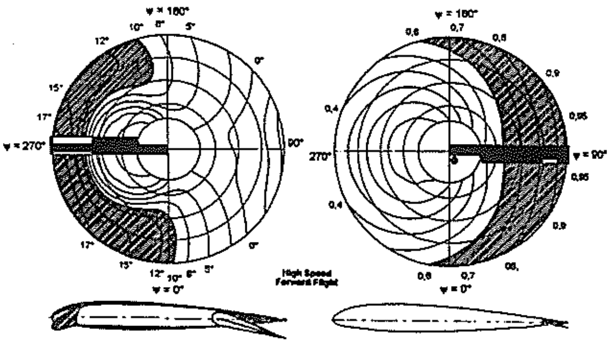

Figure 20: Several IBC-systems in the aerodynamic condition of the rotor in forward flight

The blade root control and the servo-flap principle are effective in the area of a higher dynamic pressure and do not or do barely change the airfoil. The main potential of these systems is the control of the higher blade modes normally by higher harmonic control inputs. Whereas an additional potential may result from the flap, because it controls closer at the generation of the disturbance, the disadvantage could be the necessary change of the airfoil contour at high Mach numbers.

The shown systems on the left hand side are selected with respect to a possible realization within a mid-term perspective. From a view of today, this perspective does not include a smart adaption of the airfoil, because the achieveable deformations by the existing smart material approaches are not very effective in the full scale application, and the design constraints of the blade (e.g. stiff erosion protection) prevent from smart solutions in very effective areas (e.g. adaption of nose). Therefore typical „discrete“ solutions like the direct lift flap and the nose flap are shown. In contrary to the systems on the right hand side, these systems change the airfoil decisively and are effective at a lower dynamic pressure and close to the stall limit respectively at high angles of attack.

Such a design together with a generally thinner airfoil could provide lower power consumtion and noise generation (advancing side) and provide the same or even increased blade loading due to the change of the airfoil at the retreating side.

Summarizing the potential of future IBC-Systems, the following future perspective can be summarized:

- The servo-flap is expected to be competitive to the blade root control system and may improve the potential of IBC. The RACT programme is well on the way to give a detailled answer to this topic and to develop an advanced full scale solution of a servo-flap.
- The potential for the optimization of the rotor aerodynamic (Performance, noise, stall limit) can be decisively enlarged by the adaption of the airfoil. The approaches to control the airfoil by discrete hinges (Direct lift flap, slat) will be evaluated, but they are quite difficult to realize and need a „smart solution“.
- The „smart materials“ are not yet mature for full scale application: Large deformations are not yet possible and areas of high sensitivity to small deflections (Blade nose) have special material requirements (Erosion protection). More research is needed on the domain of materials and advanced actuation systems.

7.References

1. S.T. Crews, "Rotorcraft Vibration Criteria - a New Perspective", 43rd Annual Forum of the American Helicopter Society, St. Louis, May 1987.

2. W. Johnson, "Technology Drivers in the Development of CAMRAD II", American Helicopter Society, San Francisco, California, January, 1994.

3. D. Teves et.al., "The Role of Active Control in Future Rotorcraft", 21. European Rotorcraft Forum, Saint-Petersburg Russia, pages 10.1-10.17, August 30 - September 1, 1995.

4. E.J. Davison, "The Output Control of Linear Time-invariant Multivariable Systems with Unmeasurable Arbitrary Disturbances", IEEE Transactions on Automatic Control, Vo. AC-17, No 5, October 1972.

5. W.H. Wonham, "Linear Multivariable Control", Springer Verlag, Berlin 1974.

6. M. Wasikowsky, "An Investigation of Helicopter Individual Blade Control Using Optimal Output Feedback", Thesis. Georgia Institute of Technology, November 1989.

7. B. Shahian and M. Hassul, "Control System Design Using MATRIXx", Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1992.

8. R.A. Ormiston, "Aeromechanical stability of soft inplane hingeless rotor helicopters", 3rd European Rotorcraft Forum, Aix-En-Provence, France, pages 25.1 - 25.22, September 7-9 1977.

9. Ch. Kessler, G. Reichert, "Active control of ground and air resonance including transition from ground to air", 20th European Rotorcraft Forum, Amsterdam, Netherlands, pages 64.1 - 64.17, October 4-7 1994.

10. M.D. Takahashi, "Active control of helicopter aeromechanical and aeroelastic instabilities. Dissertation", University of California, Los Angeles, 1988.

11. G. Reichert, U. Arnold, "Active control of helicopter ground and air resonance", 16th European Rotorcraft Forum, Glasgow, Scotland, pages III.6.2.1 - III.6.2.14, September 18-20, 1990.

12. F.K. Straub, W. Warmbrodt, "The use of active controls to augment rotor/fuselage stability", Journal of the American Helicopter Society, 30(3):, 13-22, July 1985.

13. N.D. Ham, "Helicopter Individual Blade Control and its applications", 9th European Rotorcraft Forum, Stresa, Italy, pages 56.1 - 56.11, September 13-15, 1983.

14. N.D. Ham, B.L. Behal, R.M. McKillip, "Helicopter rotor lag damping augmentation through individual-blade-control", Vertica, 7(4):,361 - 371, 1983.

15. Ch. Kessler, G. Reichert, "Active control to augment rotor lead-lag damping", 22nd European Rotorcraft Forum, Brighton, UK, pages 10.1 - 10.16, September 17 - 19 1996.

16. G. Tettenborn, Ch. Kessler, G. Reichert, "Comparison of IBC with active controllers using a conventional swashplate to suppress ground and air resonance", 23rd European Rotorcraft Forum, Dresden, Germany, page 13.1ff, September 16-18, 1997.

17. T. Krysinski, "Active control of aeromechanical stability", AGARD-CP-592, pages 32.1 - 32.25, April 1997.

18. F.T. Brooks, E.R. Booth, "Rotor Blade-Vortex Interaction Noise Reduction and Vibration Using Higher Harmonic Control", 16th European Rotorcraft Forum, Glasgow, September 1990

19. W.R. Splettstößer, K.J. Schultz, R. Kube, T.F. Brooks, E.R. Booth jr., G. Niesl, and O. Streby, "BVI Impulsive Noise Reduction by Higher Harmonic Pitch Control: Results of a Scaled Model Rotor Experiment in the DNW", Seventeenth European Rotorcraft Forum, Berlin, Germany, 1991

20. G. Niesl, S.M. Swanson, A.J. Jacklin, A. Blaas, R. Kube, "Effect of Individual Blade Control on Noise Radiation", pres. at the AGARD Aeroacoustic Conference, Berlin, October 1994

21. S.A. Jacklin, A. Blaas, D. Teves, R. Kube, "Reduction of Helicopter BVI Noise, Vibration, Power Consumption Through Individual Blade Control", 51st Annual Forum of the American Helicopter Society, Fort Worth, USA 1995

22. W.R. Splettstößer et.al., "Key Results from a Higher Harmonic Control Aeroacoustic Rotor Test (HART) in the German-Dutch Wind Tunnel", 21st European Rotorcraft Forum, Saint-Petersburg, 1995.

23. P. Richter, H-D. Eisbrecher, V. Klöppel, "Design and first Tests of Individual Blade Control Actuators", 16th European Rotorcraft Forum, Glasgow, 1990

24. D. Teves, V. Klöppel, P. Richter, "Development of Active Control Technology in the Rotating System, Flight Testing and Theoretical Investigations", 18th European Rotorcraft Forum, Avignon, 1992

25. S.M. Swanson, S.A. Jacklin, A. Blaas, G. Niesl, R. Kube, "Acoustic Results from a Full Scale Wind Tunnel Test Evaluating Individual Blade Control", 51st AHS Forum, Fort Worth, 1995

26. H. Schlichting, E. Truckenbrodt, "Aerodynamik des Flugzeugs", Zweiter Band, Springer Verlag

27. M. Drela, M.B. Giles, "ISES: A Two-Dimensional Viscous Aerodynamic Design and Analysis Code", AIAA 25th Aerospace Sciences Meeting, AIAA-86-0424, January 12-15, 1987, Reno, USA

28. F.K. Straub et al., "Design of a smart material actuator for rotor control, Smart Materials Structures", 6 (1997), S. 223-234

29. G. Schewe, "Force Measurements in Aeroelasticity Using Piezoelectric Multicomponent Transducers", Int. Forum on Aeroelasticity and Structural Dynamics, Aachen, June 3-6, 1991, DGLR-Bericht 91-06 (1991), 91-071.

30. G. Schewe, "Beispiele für Kraftmessungen im Windkanal mit piezoelektrischen Mehrkomponentenmeßelementen", ZFW 14 (1990), pp. 32-37.