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Development and Evaluation of Advanced Falp Control Technology Utilizing Piezoelectric Actuators

BY

P. Jänker, F. Hermle, T. Lorkowski, S.Storm, M. Christmann, M. Wettemann
DaimlerChrysler AG
Research & Technology
P.O. Box 800 465
81663 Munich
Germany

AND

V. Klöppel
Eurocopter Deutschland GmbH
81663 Munich
Germany

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Development and Evaluation of a Hybrid Piezoelectric Actuator for Advanced Flap Control Technology

P. Jänker, V.Klöppel, F. Hermle, T. Lorkowski, S. Storm, M. Christmann, M. Wettemann

DaimlerChrysler AG, Eurocopter Deutschland
81663 Munich, Germany

Abstract:

One key element of a rotor with individual blade control (IBC) based on an advanced flap control technology is a powerful and reliable actuator system. The need for highly dynamic system response, compact and robust design makes actuators based on piezoelectric materials a promising approach.

Piezoelectric materials deliver a solid-state displacement when subjected to an electric field. For successful application in mechanical subsystems this displacement normally needs to be amplified. Research efforts at DaimlerChrysler's Research and Technology Labs for Advanced Material Systems led to a highly efficient amplification mechanism that follows a rhombic, multiple frame design with no play and wear.

During extensive bench tests and when implemented in a rotor-blade segment for a three-week wind-tunnel test series, the actuator system demonstrated excellent performance and durability [1].

A further important step now is to ensure the ability of the system to withstand high centrifugal loads. The actuator itself, its mounting and the structural flap coupling have been optimized using FEM analysis tools. Again, bench tests demonstrated the functionality of the system. Results of the behavior of the piezoelectric actuator under centrifugal loads and the performance compared to the nonrotating case are presented. In addition to the test results, the test facility itself will be described, including the basic whirl tower, the energy- and data transmission system and the experimental rotating system.

1. Introduction

Some of the most urgent development tasks in the area of helicopters are to reduce noise pollution and vibrations and to enhance flight performance. An example of a promising technology that has been promoted by ECD and DaimlerChrysler Research and Technology is Active Rotor Control, which represents the key element of a future helicopter. For control purposes, trailing-edge flaps are installed in the outer part of the rotor blades which are driven by piezoelectrical actuators [3]. Control of each rotating rotor blade is effected with high speed and precision. The electronically controlled deflection of the relatively small flap causes, especially for torsionally soft designs, blade twisting with the effect of a considerable aerodynamic change in lift. The high energetic efficiency of the rotor control is based on this servo effect. For specific rotor and control data, also direct lift effects are active.

The active rotor control has four main technical objectives:

- Reduction of impulsive main-rotor noise and cabin vibrations
- Stall delay
- Stabilization of the rotor dynamics.
- Automatic blade tracking

The impulsive main rotor noise occurring during descent and manoeuver flight is excited by blade vortex interaction. This interaction is strongly reduced by increasing the misdistance between blade tip vortices and blades through local increase of the rotor downwash, e.g. by a 2/rev control input. The blade vortex interaction is detected either by pressure transducers on the blades or by on-board microphones.

For vibration reduction of a four-bladed rotor, a 3/rev, 4/rev and 5/rev control input creates "artificial" dynamic blade loads which counteract the immanent blade loads responsible for the cabin vibrations. These are measured either by strain gauges at the blade roots or by accelerometers at the main gear or in the cabin.

The stall onset can be delayed by locally decreasing the blade pitch on the retreating side. The resulting loss of moment balance and lift is compensated by a correspondingly reduced blade pitch on the advancing side and an increased pitch in the fore and aft region of the rotor azimuth. Stall onset is detected either by pressure transducers on the blades or by strain gauges on the pitch links.

For the rotor stabilization in lead-lag a feed-back of lead-lag angle and velocity leads through coupling between blade torsion, flapping and lagging to increased lead-lag damping. The lead-lag motion is sensed by strain gauges at the blade roots.

The automatic blade tracking can be attained by measuring the 1/rev unbalance in the fixed system and by introducing an appropriate constant flap angle.

For all of these methods, fast closed loop algorithms have to be applied in order to cope with the non-steady behaviour of helicopter flight.

The flap system comprises a flap with hinged supports that is driven by linear actuators. In order not to unacceptably change the nominal position of the c.g. line at approx. 25% of the blade depth, the actuator is mounted near the blade leading edge. A control rod is used for force transmission.

Controlling a flap integrated in the outer area demands a great deal of the actuator system:

- Only little installation space is available in the rotor blade. In addition, the required c.g. position of the blade at approx. 25% of the blade chord requires mass concentration in the leading-edge area.
- The high centrifugal acceleration (typically 800 - 1,000 g) results in large mass forces. Consequently, the overall weight of the actuator-flap system must be minimized.
- The actuator must cope with high air loads. The actuator dynamics must allow a 5/rev control or even higher frequencies. In the EC135 helicopter this corresponds to 35 Hz.

- The actuator system must generate sufficient stroke to control a flap deflection of ±8°. In the concrete case of an EC135, the actuator system must achieve a stroke of approx. 1 mm and a force of 2,000 N.

2. Solid State Actuator Technology

The realization of Active Rotor Control depends primarily on the performance of the actuator. Careful analysis of actuator technologies was a main focus of work at the start of the project, particularly innovative actuator technologies based on active materials.

Actuators based on mechanically active materials (smart materials) represent a new approach. Research activities in this area are being vigorously pursued in the USA, Japan and Germany. A number of alternative actuators are being considered. These can be classified according to the type of control energy needed, namely thermal actuators, i.e. elongating bodies made of polymers, waxes and SMAs (Shape Memory Alloys); electrical and magnetic actuators, i.e. piezoactuators and magnetostrictors (terfenol-D) [1]; chemical actuators, i.e. electrochemical-pneumatic actuators, pyrotechnical actuators.

Of extraordinary technical importance are electrically controlled actuators that can be integrated into electronic control systems and represent the core modules of mechatronic systems. Within this major group, piezoelectric ceramics (PZT) offer a high potential compared to the more widely used electromagnetic actuators [2].

Piezoelectrical ceramic materials convert electrical energy directly into mechanical movement. The energy conversion takes places as soon as electrical energy is applied and is limited only by the dynamics of the mechanical system. An element of piezoelectrical material constitutes an actuator in itself. From these primitive prototypes, more complex actuator constructions can be derived. For example, a flexing actuator is formed by bonding a piezoceramic plate onto a passive substrate. Block-shaped piezoelectrical elements that generate only small deflections can be advantageously combined with gear elements to form hybrid actuators.

In conclusion, the outstanding advantages of piezoelectrical actuators are their high dynamics. high deflection resolution, high force generation, high specific working capacity and simple construction.

3. Actuator Design

The required actuator stroke in the mm range with actuator forces in the range of 1,000 N is about one order of magnitude greater than the stroke capacity of previously available piezoelectrical actuators.

After having analyzed the requirements, it is seen that, from today's point of view, only piezoelectric actuators are suitable for operating a flap in the outer area of a rotor blade. The decisive technical hurdle in developing the piezoelectrically controlled flap system was the low elongation capacity of PZT materials.

Many applications in mechanical engineering demand high-performance actuators with a stroke in the mm range. Because of the low elongation capacity of piezoelectrical materials, stack actuators are unsuitable. A suitable method of construction that was developed by Daimler-Benz Research in recent years is the hybrid actuator.

A hybrid construction method, comprising a piezostack with a hydraulic or mechanical step-up gear, is suitable for actuator forces of $F_b > 500$ N. The step-up gear must meet the following requirements:

- Stiff support of the piezostack
- No mechanical play, no/slight friction
- High gear stiffness
- High energy efficiency: low elastic energy losses
- Gear ratio n - 10
- Low weight relative to the piezostack
- Production-oriented construction

A number of different designs for the implementation of a step-up gear were put forward. The influence of the mounting frame alone on the overall performance of the hybrid actuator is discussed below with the aim of revealing the limitations of the hybrid construction method.

An important criterion of the quality of a design as regards working capacity is the mechanical efficiency η_{MECH}, which is defined as the ratio of the working capacity of the hybrid actuator (W_H) to the working capacity of the piezo (W_P):

$$\eta_{MECH} = W_H / W_P \qquad (1)$$

Assuming that the stroke at the mechanical output corresponds ideally to the theoretical transmission ratio n and is not reduced by restoring elastic forces, the mechanical efficiency is defined solely by the ratio of the real to the theoretical blocking force at the mechanical output (F_{HR} and F_{HT}):

$$\eta_{MECH} = F_{HR} / F_{HT} \qquad (2)$$

The reduction of the blocking force is calculated from the ratio of the overall stiffness of the mechanical series connection of the stack (S_P) and frame (S_R) to the stiffness of the piezostack alone:

$$\eta_{MECH} = F_{HR} / F_{HT} = (1 + S_P / S_R)^{-1} \qquad (3)$$

In order to increase the efficiency, greater stiffness of the frame (and gear) is required. However, massive and voluminous construction is not desirable, as a low overall weight is the objective. A high specific working capacity is aimed at. A further important criterion of the design quality is therefore applied, namely the mass efficiency η_{MASS}, the ratio of the specific working capacity of the hybrid actuator and piezostack:

$$\eta_{MASS} = \eta_{MECH}\, m_H / m_P \qquad (4)$$

To arrive at an estimate, the frame is assumed to be a prismatic rod as long as the piezostack. The frame data are scaled with respect to the piezostack:

$$a := A_R/A_P$$
$$y := Y_R/Y_P$$
$$r := \rho_R/\rho_P$$

where:

R,P	=	index frame, piezo
A	=	cross-sectional area
Y	=	Young's modulus
ρ	=	mass density

The base plates are neglected. Hence, the mechanical efficiency and the mass efficiency are calculated as follows:

$$\eta_{MECH} = (1+a^{-1} r^{-1})^{-1} \quad (5)$$

$$\eta_{MASS} = (1+a\,r)^{-1}(1+a^{-1} y^{-1})^{1} \quad (6)$$

The mass efficiency reaches a maximum for the relative cross section $a_{OPT} = (ry)^{-0.5}$. For steel, a_{OPT} is 43%, assuming a Young's modulus for the piezoceramic material of 38 Gpa. The maximum mass efficiency η_{MASS} is 48%.

Designing the frame cross section to be larger than the cross-sectional ratio a_{OPT}, which is optimal with regard to the mass efficiency, is in any case expedient. Above a_{OPT} there is a conflict of goals between mass efficiency and mechanical efficiency.

In view of this compromise, the working capacity is assessed higher, as the technical (electrical power supply) and the economic price of the piezo is always higher than the effort involved for the mechanics.

An integrated design is considered to be the optimum construction method for a weight- and volume-optimized hybrid actuator. The stiff mounting frame, which is required in any case, is designed by the integration of joints as a gear. In order to prevent play and wear, flexures are used as joints. Fig. 4 shows the diamond-shaped geometry of the gear.

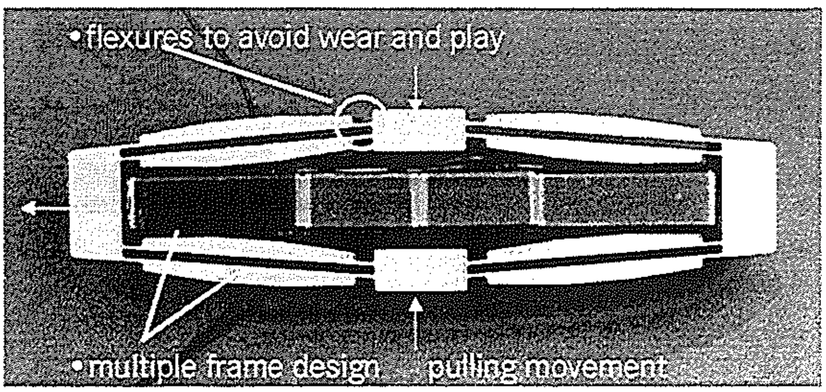

Figure 1: DWARF

Due to the geometric arrangement, an expansion movement of the piezostack is transformed into a pulling movement. Critical elements of the design are the flexures that are loaded in the movement and bending directions. The flexures act as a spring load on the piezostack to reduce the free stroke. At the same time, the flexures are a determining factor for the stiffness S_R of the frame. A compromise must be made between high axial stiffness and low bending stiffness. At the same time, the material load with respect to the joints (axial tension and bending) must be designed so as to achieve high fatigue strength.

The efficiency of the gear was optimized by designing it as a multiple frame. With high axial frame stiffness, the bending stiffness of the joints is reduced, the material load on the joints is decreased and the stroke is increased.

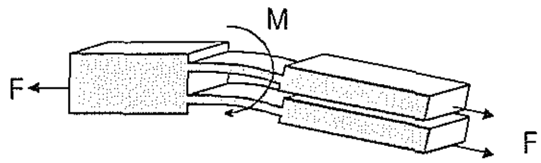

Figure 2: Multiple frame. Joint area.

With n-fold subdivision of the frame, the bending stiffness is reduced by a factor n^{-2} and the boundary fiber elongation by n^{-1}. The detailed computational optimization of the DWARF system was effected using analytical methods and FEM. The dynamics of the hybrid actuator are very good, with the first resonance frequency occurring at 220 Hz.

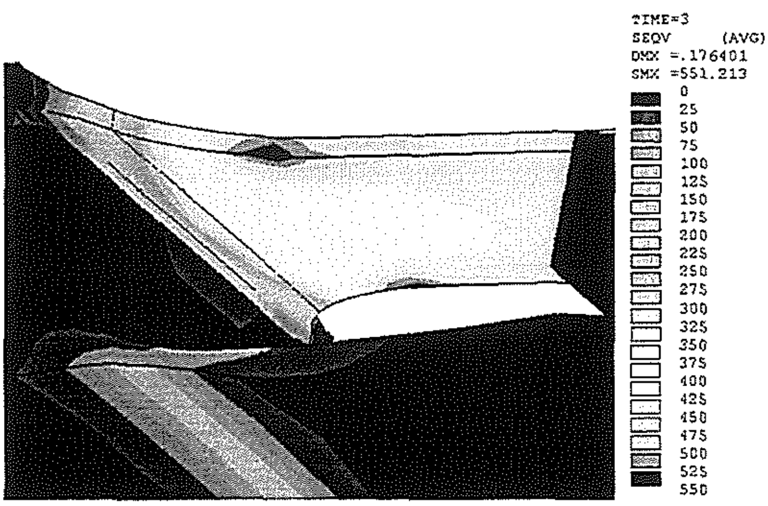

Figure 3: FEM calculation. Detailed study of the joint area.

The performance data of the DWARF actuator were decisively improved over several development phases. The main characteristic data at present, determined at 35 Hz, are given below:

- Blocking force 780 N
- Free stroke 1.26 mm
- Mechanical efficiency 83%
- Mass efficiency 33%
- Mass 400 g

The thermal expansion of the piezoactuator over an extended operating-temperature range must be taken into consideration. The thermal expansion coefficients of the frame and the piezo can be adjusted by selecting suitable materials or material combinations.

4. Flap Design

The pursued design comprises a hinged flap that is driven by a linear activator via a control rod. Fig. 4 shows the actuator integrated in a wind-tunnel model. Four actuators are mounted near the blade leading edge. Two flap halves are driven via control rods. This arrangement is consistent with the requirement that the c.g. line must be at about 25% of the blade depth.

The flap stroke is controlled via a dual-circuit electronic system. An outer control circuit analyzes the signals relating to the flight state and relays a correct path to the inner control circuit. In the inner circuit, a processor analyzes a flap-deflection signal from a sensor and generates a control signal that is transmitted to the piezoelectrical actuators via a power output. The inner circuit compensates for the effects of hysteresis and friction as well as for external loads and perturbations and ensures a linear relationship of the control signal and flap stroke. Key elements of this technology are the power generators. Installation space is restricted, and only low construction weight is allowed. Moreover, the power consumption must be kept low. For these reasons, only switching amplifiers come into consideration as power outputs for recovering the electrical energy stored in the piezoactuators and thus minimizing net consumption from the onboard power supply.

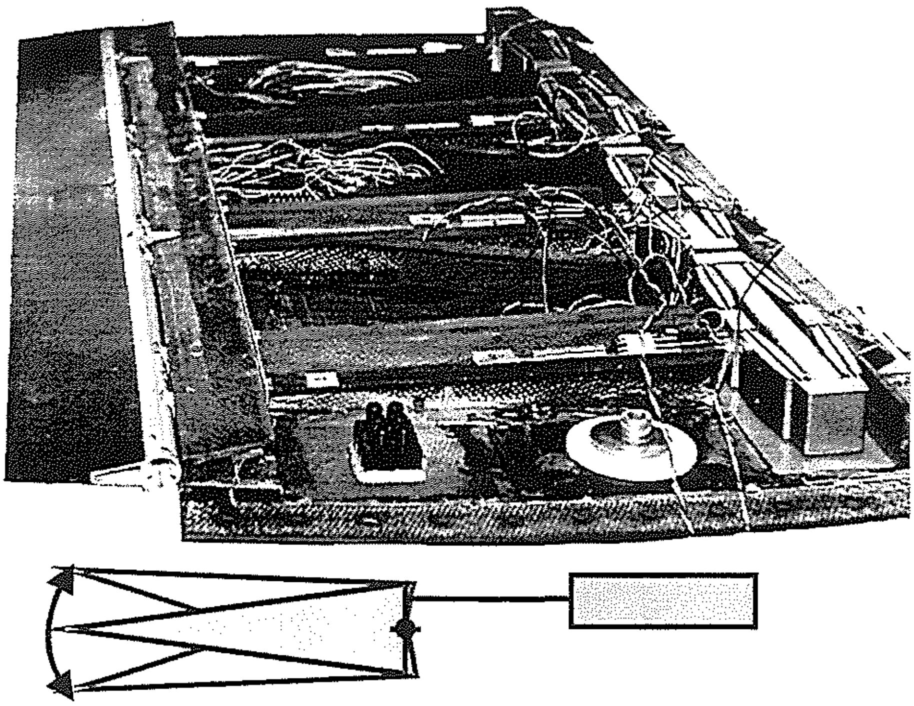

Figure 4: Wind-tunnel model. View of the actuator-flap module.

5. Test Procedure

The newly developed flap technology was subjected to an extensive test series. The procedure is divided into the following phases:

- Electromechanical characterization of the piezoelectrical actuators
- Characterization and fatigue testing of the DWARF actuators
- Performance test of the actuator-flap module
- Wind-tunnel tests
- Tests of the DWARF actuators on a rotational test bed

Important milestones of the project are the attainment of sufficient performance in the wind tunnel and the demonstration of mechanical strength in the centrifugal field.

5.1 Wind-tunnel tests

A rotor-blade segment fitted with a flap-actuator module was subjected to an exhaustive two-week test series in a wind tunnel. The aim of the tests was to demonstrate sufficient authority of the piezoelectrical actuators under realistic aerodynamic loads and to clarify the basic aerodynamic relationships [3]. The tests successfully demonstrated the suitability of the flap technology. The system operated flawlessly throughout the entire period.

5.2 Centrifugal Testing

In later use in a rotor blade, the actuators will be subjected to extraordinarily high mechanical loads as a result of centrifugal acceleration. After detailed mathematical analysis and design work, an actuator was tested on a rotational test bed (Fig. 5).

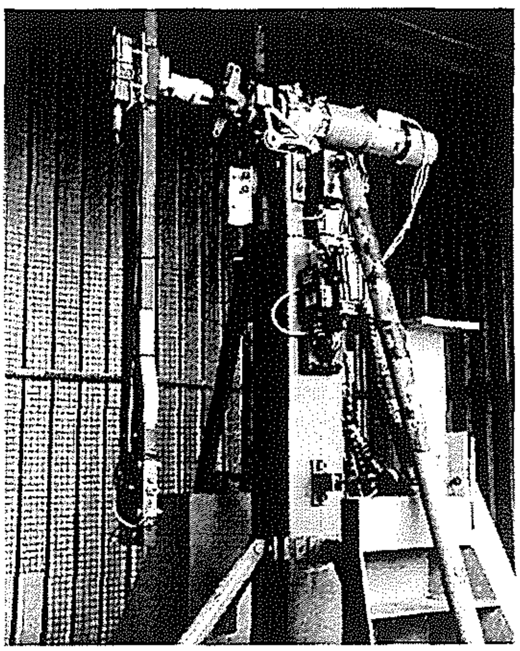

Figure 5 Test bed for the centrifugal test.

The DWARF actuator was mounted inside a rotating arm. During rotation, the actuator was controlled via an electrical slip ring. Measurement signals for the actuator force and path were transmitted to the stationary system and recorded. The illustration below presents a sample of measurements of the blocking force, showing constant behavior across operating frequency and rotational speed. The rotation tests demonstrated adequate strength of the DWARF actuator for use in a rotor blade. Successful conclusion of the rotational tests marked an important milestone in the project.

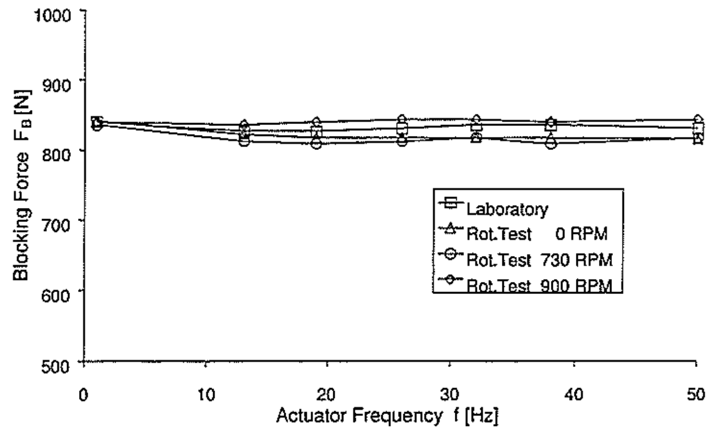

Figure 6: Measurement of the blocking force of the DWARF actuator during centrifugal testing. 900 rpm, corresponding to a centrifugal acceleration of 800 g

6. Conclusion

An innovative flap-control technology is being developed for future helicopters. At the heart of the technology is a piezoelectrical actuator. The high-performance DWARF actuator was designed to drive a flap integrated in a rotor blade and was optimized in terms of energy and mass efficiency as a figure of merit. Detailed tests, including rotational tests, demonstrated the basic suitability of the system. In the next step, full-scale rotor blades will be fitted with this new technology and tested on a whirl tower. Subsequently, it is planned to test the rotor equipped with high-frequency flap control in flight. Up to the stage of production maturity, special challenges will be to demonstrate the reliability and service life of the piezoelectrical actuators under realistic load conditions.

References:

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