ACTUATOR TECHNOLOGY BASED ON SMART MATERIALS FOR ADAPTIVE SYSTEMS IN AEROSPACE

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Abstract

Any new aerospace development has to incorporate a large number of mechanical servo functions, and the range of these functions and requirements in servo technology is growing apace. New actuator technologies therefore give fresh impetus to product development and accelerate progress. Actuators based on mechanically active materials are a new and attractive approach. This category of actuators utilizes materials effects such as piezoelectricity allowing to deform a body by the control of external parameter such as the electrical voltage applied.

1 Introduction

Technical systems, including aerospace products, are normally subject to a multitude of compromises during their design process. Offdesign operation or constantly changing environmental conditions lead to non-optimal performance. A continuous adjustment by intelligent variation of system characteristics should help to substantially improve performance, safety and comfort. Adaptation has been mother nature's most successful survival strategy after all.

Sensors, signal-processing, and actuation devices are the three core components of adaptive systems. Actuator technology has not kept pace with the rapid development microelectronics has experienced in recent years. Piezoelecric actuators represent a new technology that offers a host of advantages. In combination with signal-processing electronics, the good mechanical and electrical integratability of piezoelectric actuators make these devices key elements in innovative, intelligent systems. Showing solid-state characteristics piezoceramics deliver high-precission and fast-response displacement.

Research efforts at DaimlerChrysler's Research and Technology Labs for Advanced Material Systems have led to a number of sophisticated actuator designs. Ranging, from 10 -10000 Newtons blocking force and 0.1 - 1.5 mm. free displacement overall actuator performance can be custom tailored to specific application needs. For optimum system design thorough characterization of piezoelectric actuator elements is required. To this end specific static and dynamic measurement methods were developed to characterize the elements under temperature and load influences.

Helicopters represent an ideal platform to promote this attractive technology. Future helicopter generations are expected to radiate less noise, offer vibration-levels equal to smooth airplane riding comfort, increased safety, expanded flight envelope, and lower maintenance and operation costs, where some of these aspects might be desirable in other aerospace applications too. In cooperation with Eurocopter Deutschland a number of systems based on piezoelectric actuator technology are developed.

Individual Blade Control (IBC) for noise and vibration reduction is achieved by integration of a fast-response trailing-edge flap driven by piezoelectric actuators. This system has been extensively tested in Wind-Tunnel and rotational experiments. For suppression of body noise submitted from the gear box onto the passenger cabin smart struts with surface mounted piezoelectric shells have been applied. An adaptive, frequency variable vibration absorber model with a tunable spring is demonstrated.

2 Piezoelectric Actuator Systems

2.1 Material Charactization

The aim of a metrological investigations is to support product development with application-oriented data. In order to describe the material behavior, a model of the electro-mechanical behavior is required.

In contrast to the idealized linear model, the real behavior of piezoelectric materials is nonlinear and subject to hysteresis. Complete characterization demands from the mechanical point of view a description of the behavior in the three-dimensional space elongation-force electric voltage (X, F, U), and from the electrical point of view a description in space of charge-electric voltage-force (Q, U, F). The most important parameters are temperature and frequency.

In order to ensure characterization of piezoactuators that is as complete as possible, a measurement stand with an active measuring head was developed (Fig. 1). The measurement stand comprises an extremely stiff frame with axial optical access on both sides to the object to be measured, hydraulics to preset a static force component, a differential optical length-measuring system, force measurement and a temperature chamber.

The active test head is equipped with piezoelectric actuators. Electronic control permits representing various external load situations by controlling the active test head. For a measurement, a transient electric voltage is predefined and the temperature set so as to be constant. The change in length of the actuator and of the electric current is measured. The absorbed and dissipated electric energy as well as the large-signal impedance (large-signal capacity and power factor) are calculated in the evaluation.

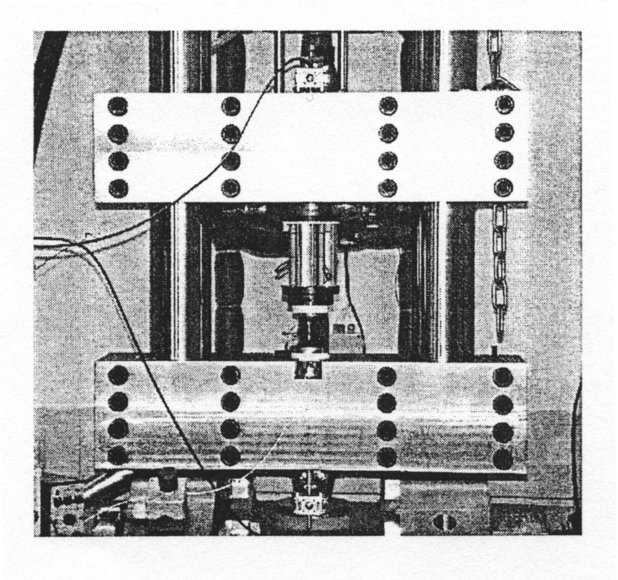

Fig. 1: Dynamic measurement stand with active test head. Determination of the behavior X(F,U) and Q(F,U) at a constant temperature.

The force generated is measured (blocking-force measurement) with infinitely stiff clamping or with a constant length, respectively, of the piezoactuator under test. The free deflection is determined with ideally flexible clamping or a constant force, respectively. Besides these extreme load situations, further processes such as variable spring loads can be represented using the test head (Fig. 2).

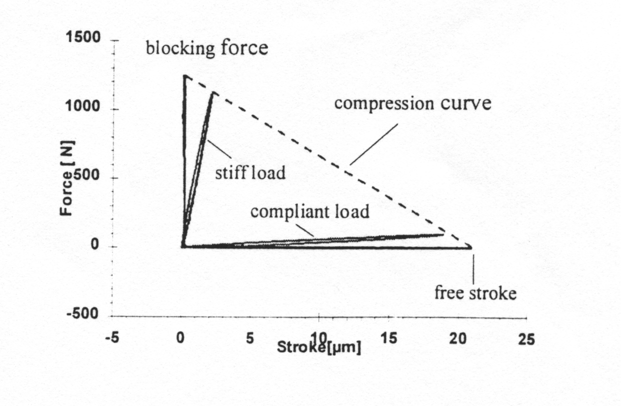

Fig. 2: Results of measurements on the dynamic test stand.

2.2 Hybrid Actuator Design

A variety of applications in mechanical engineering demand high-performance actuators with a stroke in the mm. range. Due to 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 stepup gear, is suitable for actuator forces 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

In order to implement a step-up gear, a variety of differing designs was put forward. With the aim of indicating the limitations of the hybrid construction method, the influence alone of the mounting frame on the overall performance of the hybrid actuator will be discussed in the following.

An important criterion of the quality of a design as regards the 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 in an ideal way to the theoretical transmission ratio n and is not reduced by restoring elastic forces, then the mechanical efficiency is solely defined 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 yielded from the ratio of the overall stiffness of the mechanical series connection of 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 hybrid actuator and piezostack:

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

In order to permit of a calculatory estimation, the frame is assumed to be a prismatic rod as long as the piezostack. The frame data are scaled with respect to the piezostack:

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

with:

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:

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

$$\eta_{MASS} = (1 + ar)^{-1} (1 + a^{-1} y^{-1})^{1} \qquad (6)$$

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

Designing the frame cross section so as 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 will be 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 through the integration of joints as a gear. In order to ensure freedom from play and wear, flexures are used as joints. Fig. 3 shows the diamond-shaped geometry of the gear.

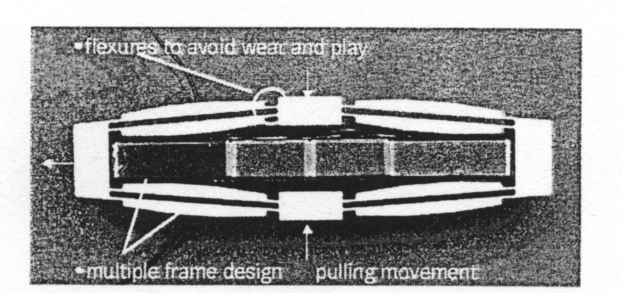

Fig. 3: DWARF - Hybrid Actuator

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 movement and bending directions. The flexures act on the one hand as a spring load on the piezostack and reduce the free stroke. On the other hand, 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 fatigue strength.

The effectivity of the gear was optimized decisively by being designed as a multiple frame (Fig. 4). With high axial frame stiffness, the bending stiffness of the joints is reduced, the material load on the joints is decreased and the stroke increased. The detailed computational optimization of the DWARF system was effected using analytical methods and FEM.

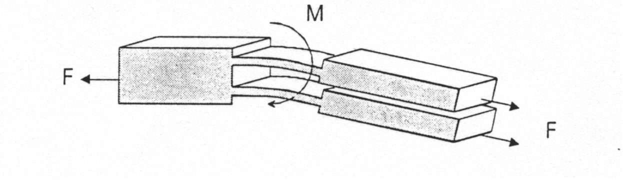

Fig 4: Multiple frame. Joint area.

With n-fold subdivision of the frame, 2 the bending stiffness is reduced by a factor n- and the boundary fiber elongation by n-l. The dynamics of the hybrid actuator is very good, the first resonance frequency lies at 220 Hz.

DWARF data:

Blocking force	720 N
Free stroke	1.1 mm
mechanical efficiency	83%
Mass efficiency	33%
Mass	400 g

The thermal expansion of the piezoactuator is to be taken into consideration with an extended operating-temperature range. The thermal expansion coefficients of the frame and the piezo can be adjusted through suitable material selection or material combinations, respectively.

3 Aerospace Applications

3.1 Active Flap for Rotor Control

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. 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 feedback 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 fight.

The flap system comprises a flap with hinged supports that is driven by linear actuators. In order not to unacceptably chance the nominal position of the e.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 e.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. 1mm and a force of 2,000 N.

The pursued design comprises a hinged flap that is driven by a linear activator via a control rod. Fig. 5 shows the actuator integrated in a windtunnel 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.

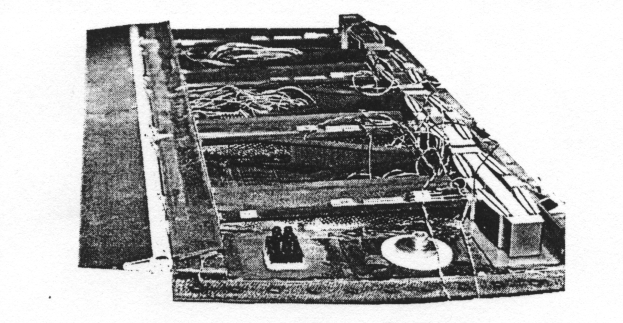

Fig. 5: Wind-tunnel model. View of the actuator-flap module.

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.

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. The tests successfully demonstrated the suitability of the flap technology. The system operated flawlessly throughout the entire period.

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. 6).

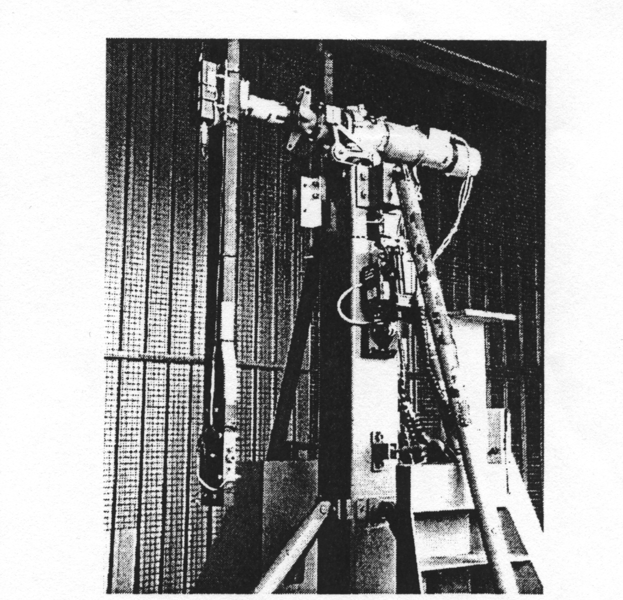

Fig. 6: Test bed for the centrifugal test.

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.

3.2 Adaptive Vibration Absorber

A further application example of a mechatronic system with piezoelectric actuators is a frequency- variable vibration absorber. Sound and vibrations are undesirable side effects of mechanical systems. People's health and wellbeing are impaired and machinery lifetime reduced. Where it is not possible to reduce the origin of the disturbance at the source itself, vibrations are combated with secondary measures such as vibration absorbers.

There are a whole host of applications in technology. for these absorbers. They are used widely in automobiles. In helicopters they are installed in the passenger cabin to suppress strong 4/rev vibrations generated by the main rotor. The future use of helicopters made by the ECD company envisages a frequency variation of the main rotor of +/- 3% and requires a frequency-variable absorber. Up to now, frequency-variable absorbers involved great cost and effort. An elegant technical solution has now succeeded on the basis of a structure-integrated piezoactuator system.

A conventional vibration absorber is shown in .the diagram in Fig. 7. The structure to be stabilized is represented as a spring-mass system.

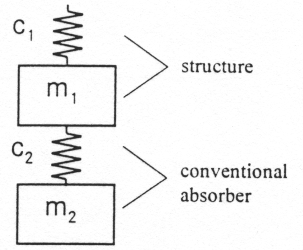

Fig. 7: Diagram of a vibration absorber.

The vibration absorber's task is to establish a vibration node at the location of the structural mass m_1 and to reduce the vibration amplitude to zero. A simple mass-spring oscillator fulfills this task in the resonance frequency. In order to maintain vibration absorption outside the resonance frequency, an actuator must serve to generate a correcting force.

A solution based on a piezoelectric actuator is represented in Fig. 8. Thin piezoceramic plates are mounted on the leaf spring of the vibration absorber. A sensor signal with respect to the dynamic deflection of the leaf spring is gained by tapping the electrode on a thin ceramic plate. The sensor signal is amplified and supplied to the actuator plates. The thin piezoelectric plates generate a force proportional to the stroke which, in addition to the elastic force of the spring, acts on the absorber mass. Outwardly, the spring acts with a changed stiffness. Setting the amplification gain means that the spring stiffness is controlled D(gain) and the system tuned.

$$\omega(gain) = \sqrt{\frac{D(gain)}{m_2}} \qquad (7)$$

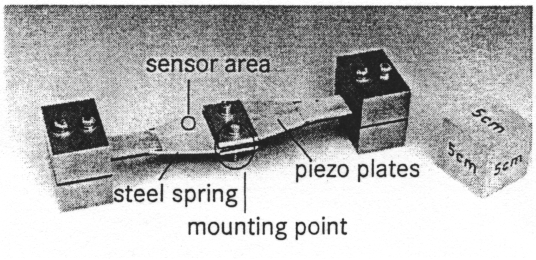

Fig. 8: Adaptive vibration absorber

With an absorption force of 100 N, the functional model shown in Fig. 7 can be tuned via the frequency range of 28 Hz to 39 Hz.

4 Conclusion

Actuators are key elements of advanced adaptive mechanical systems. Actuators based on piezoelectrical materials are extremely promising candidates for implementing adaptive mechanical systems in vehicle construction. A current application example is active rotor control for helicopters. Previous piezoelectrical actuators often feature a stroke capacity that is too low. This contribution presents an effective construction method for high-performance piezoactuators with a high stroke capacity. It has been shown that constructing energy-efficient piezoelectrical actuators with strokes in the mm range and forces in the kN range is possible.

A second application example is an adaptive vibration absorber based on piezoelectric ceramics. This frequency-variable vibration absorber features a particularly simple design. The core piece of the frequency-variable mechanical resonator is a spring with virtually variable stiffness. In this system, the actuatory as well as the sensory piezoelectric effect is exploited.

By means of two application examples, the article demonstrates the promising potential inherent in piezoelectric actuators for innovative mechatronic system solutions.

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