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Mechatronics Using Piezoelectric Actuators

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Abstract

Mechatronics has enabled "intelligent" machinery such as car antiskid braking systems to be created. Any new automotive development has to incorporate a large number of mechanical servo functions, and the range of functions and requirements in servo technology is growing apace. New actuator technologies, therefore, give fresh impetus to product development and accelerate progress. Piezoelectric 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. This paper presents prototype applications. Particular attention is focused on powerful large-displacement piezoelectric actuators. The article also includes concrete characterization of piezoelectric actuator elements. To this end specific static and dynamic measurement methods were developed to characterize the elements under temperature and load influences. © 1999 Elsevier Science Limited. All rights reserved

Keywords: mechatronic, piezoelectric properties, mechanical properties, PZT, actuators.

1 Introduction

Over the past few years, above all, microelectronics has shaped and accelerated technical developments. Modern electronics makes it possible to realize 'smart' adaptive systems. These systems cover operating conditions with sensors, further process the information to actuator commands and, by means of actuators, control mechanical vehicle subfunctions. Developments in the area of actuator systems have not kept pace at all with microelectronics and sensor systems.

Actuators based on mechanically active materials (smart materials) are a new approach toward closing this technological gap. Lively R&D activities can be observed in the USA, Japan and Germany. A variety of alternative actuators are being considered in this connection which can be classified according to the type of control energy, namely thermal actuators: elongating bodies made of polymers, waxes and SMAs, Shape Memory Alloys; electrical and magnetic actuators: piezoactuators and magnetostrictors (terfenol-D);[1] chemical actuators: electrochemical-pneumatic actuators, pyrotechnical actuators.

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

2 Metrological Characterization of Piezoactuators

The aim of 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. A customary model is a linear equation system.

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

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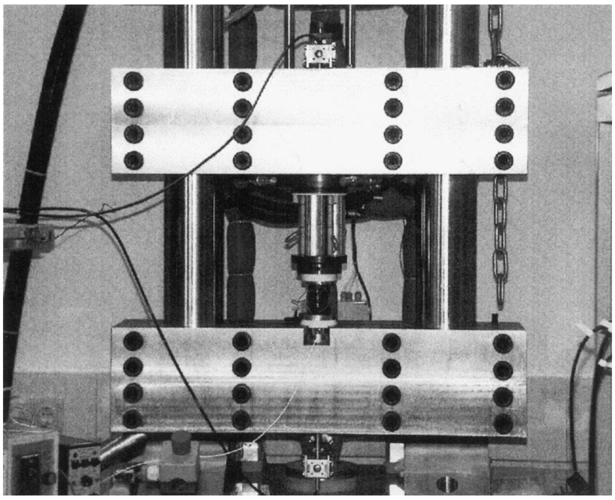

Fig. 1. Dynamic measurement stand with active test head. Determination of the behavior X(F,U) and Q(F,U) at a constant temperature.

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 allows the representation of 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.

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.

3 Application Examples

The industrial application technology of piezoelectrical actuators is currently in an early development stage. Piezoelectrical actuators are not yet available in the large quantities found in the consumer goods industry (e.g. auto construction). Applications in aviation, with relatively small quantities, are consequently of initial interest. Helicopters represent a platform of this type. Helicopters are vehicles with unique application possibilities. A number of advanced technical developments are still required in order to open up further market segments. Urgent development tasks are to reduce noise pollution and vibrations and to enhance flight performance.

Examples of solution-offering technologies that have been promoted by ECD and Daimler-Benz Research and Technology comprise the:

- active rotor control, and
- adaptive vibration absorber

3.1 Active rotor control

The key element of a future helicopter is active rotor control. For control purposes, servoflaps are installed in the outer part of the rotor blades which are driven by piezoelectrical actuators.[3]

Controlling each rotor blade is effected during a rotor revolution with high speed and precision. The electronically controlled deflection of the relatively small flap causes 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.

The active rotor control has three main technical objectives:

- reduction of main-rotor noise and cabin vibrations;
- improvement of the rotor aerodynamics;
- stabilization of the rotor dynamics.

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 lot 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 depth requires mass concentration in the leading-edge area.
- The high centrifugal acceleration (typ. 1000 g) results in large mass forces. Consequently, the overall weight of the actuator-flap system must be minimized.
- The actuator must cope with the high air loads. The actuator dynamics must be better than 5/rev. This corresponds with the EC135 helicopter 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 blocking force of 2000 N.

The required actuator stroke in the mm range with actuator forces in the range of 1000 N is about one order of magnitude higher than the stroke capacity of previously available piezoelectrical actuators. After having analyzed the requirements, it is seen that, from today's point of view, solely piezoelectric actuators are suited to drive 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 the PZT materials.

3.2 Large displacement, high force actuators

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 step-up 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}):

$$\eta_{\mathrm{MECH}} = W_{\mathrm{H}}/W_{\mathrm{P}} \tag{1}$$

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}):

$$\eta_{\mathrm{MECH}} = F_{\mathrm{HR}}/F_{\mathrm{HT}} \tag{2}$$

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:

$$\eta_{\mathrm{MECH}} = F_{\mathrm{HR}}/F_{\mathrm{HT}} = (1 + S_{\mathrm{P}}/S_{\mathrm{R}})^{-1} \tag{3}$$

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:

$$\eta_{\mathrm{MASS}} = \eta_{\mathrm{MECH}} m_{\mathrm{H}}/m_{\mathrm{P}} \tag{4}$$

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: $= A_{\mathrm{R}}/A_{\mathrm{P}}$
y: $= Y_{\mathrm{R}}/Y_{\mathrm{P}}$
r: $= \rho_{\mathrm{R}}/\rho_{\mathrm{P}}$

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:

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

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

The mass efficiency reaches a maximum for the relative cross-section $a_{\mathrm{OPT}} = (ry)^{-0.5}$. 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.

3.3 Design of the actuator system

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. Figure 4 shows the diamond-shaped geometry of the gear.

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.

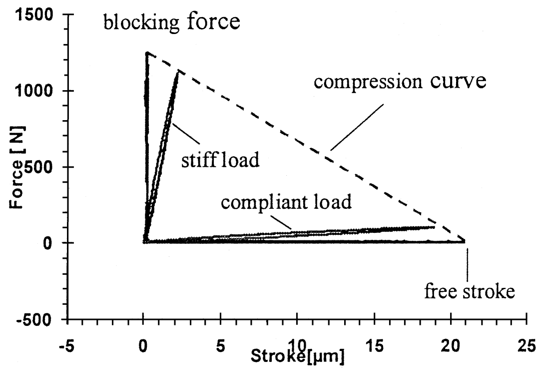

Fig. 2. Results of measurements on the dynamic test stand.

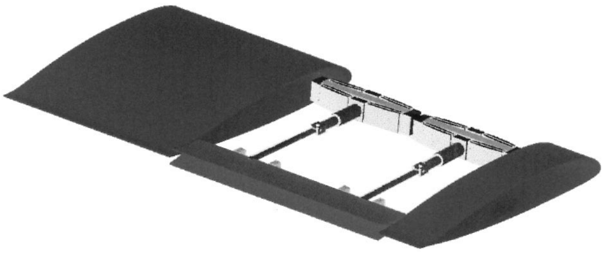

Fig. 3. Rotorblade segment with integrated actuator flap unit.

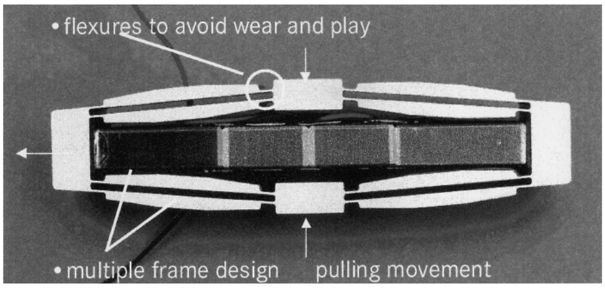

Fig. 4. DWARF.

The effectivity of the gear was optimized decisively by being designed 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 increased. The detailed computational optimization of the DWARF system was effected using analytical methods and FEM.

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 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.

3.4 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 well-being 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

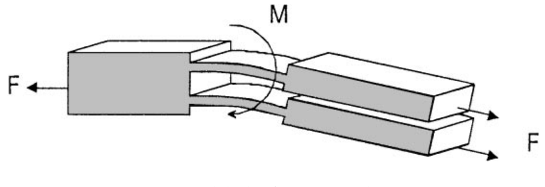

Fig. 5. Multiple frame. Joint area.

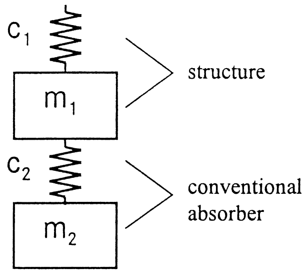

Fig. 6. Diagram of a vibration absorber.

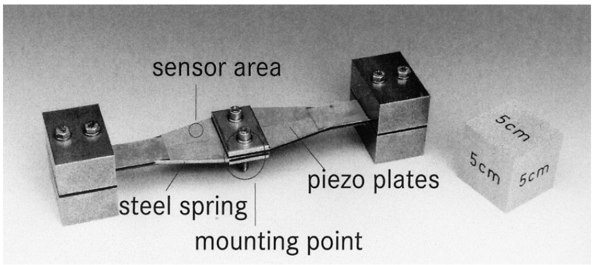

Fig. 7. Adaptive vibration absorber.

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. 6. The structure to be stabilized is represented as a spring-mass system.

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. 7. 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.

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

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

4 Conclusions

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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