DESIGN, MANUFACTURING AND EXPERIMENTAL EVALUATION OF A MAGNETOSTRICTIVE ACTUATOR FOR ACTIVE VIBRATION CONTROL AND DAMAGE ANALYSIS

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Abstract:
Magnetostrictive actuators show great potential due to their high forces and short reaction times for applications on heavy and stiff structures such as those found in aeronautics, civil structures and machine tools. The potential of the magnetostrictive technology has been utilised and investigated in a recently finalised European Brite-Euram project called MADAVIC (Magnetostrictive Actuators for Damage Analysis and Vibration Control). In this paper, the design, manufacturing and experimental evaluation of a magnetostrictive actuator for vibration control and damage analysis applications are presented. Special attention is focussed on magnetic and mechanical design aspects to increase the actuator performance. Optimised placement of permanent magnets in the magnetic circuit and the use of a proprietary force outlet design result in a highly homogeneous magnetic bias field in the active material. Furthermore, improved manufacturing methods and the use of standard components reduced cost and weight of the resulting prototype. The results of an experimental actuator evaluation validate the design specifications derived from the vibration control and damage analysis applications.

Introduction

Magnetostrictive actuators show great potential in applications of active vibration control and damage analysis on heavy and stiff structures due to their high forces and short reaction times. In a recently finalised European Brite-Euram project called MADAVIC (Magnetostrictive Actuators for Damage Analysis and Vibration Control), several magnetostrictive actuators were developed and built for application on aeronautic and civil structures.

A magnetostrictive actuator is an electromechanical device in which magnetic and mechanical design aspects are crucial for achieving effective use of the active material. Permanent magnets are commonly used in magnetostrictive actuators to set the magnetic operating point, thereby reducing or eliminating the need for a bias coil current and subsequently reducing power losses. The optimal placement of the permanent magnets and the guidance of the magnetic flux are critical design criteria to achieve a homogenous magnetic bias in the active material at the desired level. The complexity of magnetic circuits demands the use of effective simulation tools, such as those based on the finite element method, to achieve an optimal solution. The pole piece or actuator force outlet forms the junction of the magnetic circuit with the mechanical output of the actuator and must therefore fulfil both magnetic and mechanical requirements.

Technical specifications regarding output force and displacement, bandwidth and actuator weight were derived from the applications of vibration control and damage analysis on aeronautic and civil structures. The actuator should achieve a free (no-load) displacement of ±25 µm, a blocking force of ±5000 N and a cut-off frequency of 100 Hz. The weight should be minimised. An active rod of modified Bridgman Terfenol-D with a length of 50 mm and a diameter of 20 mm was selected based on the force and displacement requirements. This paper will discuss the optimisation of the magnetic circuit addressing in particular the placement of the permanent magnets and the force outlet design. Manufacturing aspects will also be mentioned. The experimental measurement of the actuator will then be presented together with the achieved results. Finally, the conclusion will acknowledge the suitability of the actuator design for the mentioned fields of application.

Magnetic circuit design

Analogue to an electric circuit in which conductors transport the electrical energy to the loads, the magnetic circuit of a magnetostrictive actuator guides the magnetic flux generated by the coil and permanent magnets to the magnetic load, i.e. the magnetostrictive rod. The magnetostrictive actuator topology shown in Fig. 1 formed the basis for optimisation work. As in one of three magnetic circuit arrangements presented by Schäfer [1] and similar to the design by Wakiwaka et al [2], the permanent magnets were placed in the return path outside of the coil. A cylindrical magnetic circuit design was selected for its symmetry, which provides enhanced magnetic shielding, exhibits particular manufacturing benefits and is easier to simulate.

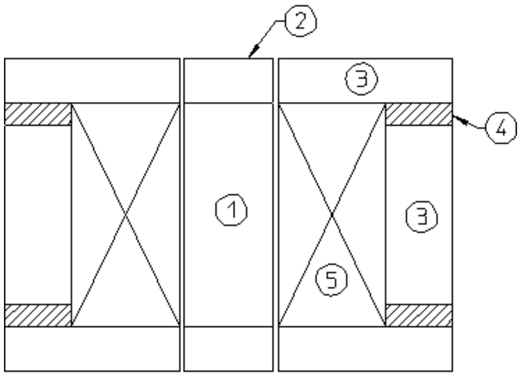

Fig. 1: *Schematic of actuator construction: 1) magnetostrictive rod, 2) mechanical force outlet, 3) magnetic coupler, 4) permanent magnets and 5) driving coil.*

Requirements placed on the magnetic circuit include low reluctance and of course effective guidance of the magnetic flux to create a homogenous magnetic field in the active rod. NdFeB magnets were selected due to their high coercive field strength, which permits the use of thin magnets for minimising the overall magnetic circuit reluctance, as well as their temperature stability. The magnetic circuit couplers were constructed of 0.35-0.5 mm thick silicon-iron sheet, a material commonly used in power transformers to reduce eddy current losses. The laminate material is arranged to benefit the magnetic flux into the rod: the sheets in the coupler pieces located above and below the coil are arranged horizontally while the couplers located outside of the coil are created from wound sheet resulting in cylindrical laminations.

Design of force outlet

The actuator force outlet design is based on the results of a magnetic and mechanical evaluation study presented previously [3]. The mechanical force outlet was divided into two laminated components, a plate and a conical cylinder, to achieve an effective guidance of the magnetic flux and minimise eddy current losses. The conical cylinder is constructed of soft magnetic laminates parallel to the rod axis and is mounted in the plate with laminates perpendicular to the rod axis. Therefore, the magnetic flux lines should be guided in such a way that they will not cross any laminations during the entrance to the active material. The result should be a minimum of eddy current losses in the force outlet and a more homogeneous magnetic flux in the rod along the symmetry axis. Furthermore, the resulting force outlet should form a stiff, mechanical entity with low damping.

This design was evaluated using both magnetic and elastic finite element analyses. The results of the magnetic study imply a significant reduction of eddy current losses with respect to a non-laminated force outlet design, since the majority of the magnetic flux is parallel to the laminates. The elastic finite element calculations also showed that the estimated mechanical stiffness of the new mechanical entity should be just 3-4% lower than a solid mechanical force outlet. For details of this design, see [3].

Results of magnetic simulations

The cylindrical actuator design allowed the magnetic circuit to be modelled in two dimensions with axial symmetry. Simulations were performed with a finite element solver. The magnetic couplers and force outlet were defined with non-isotropic magnetic properties to model the lamination [3]. All material properties were assumed to be linear, which is an acceptable assumption as long as the flux density remains below the saturation level.

The desired level of magnetic bias was already achieved in the first magnetostrictive actuator design version. However, the large size of the magnetic circuit and inhomogeneity of the field in the active rod were cause for optimisation. Several design and simulation iterations resulted in a more compact magnetic circuit design with improved field homogeneity in the magnetostrictive rod for the second and third actuator versions. The two-piece force outlet design and elbow-like connection of the coupler pieces make a significant contribution in guiding the magnetic flux, see Fig. 2. In fact, the resulting magnetic field deviation from the mean field strength along the length of the rod is on the order of just 2%, see Fig. 3.

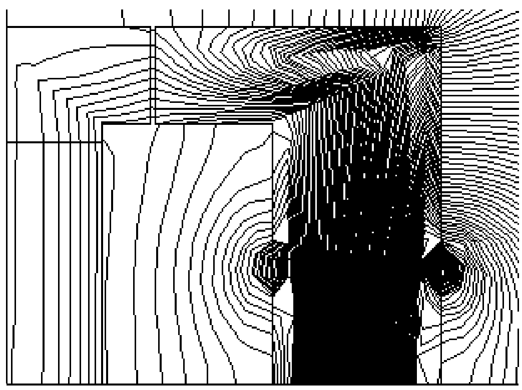

Fig. 2: *Magnetic flux lines in the optimised magnetic circuit (quarter model with symmetry axis at left).*

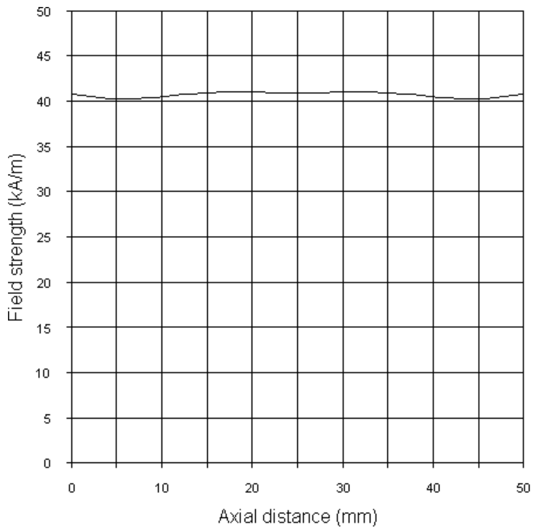

Fig. 3: *Axial magnetic field distribution within the active material.*

Fig. 4: *Prototype of a commercially available magnetostrictive actuator.*

Manufacturing aspects

Manufacturing simplicity and commercial availability of components were driving forces during the design optimisation of the magnetic circuit and the housing. Each development step led to an improvement in mechanical design without compromising actuator performance. A weight reduction of 50% over the first actuator version was achieved.

The outer segments of the magnetic circuit were created using commercially available laminate coils, while the horizontally arranged magnetic couplers and elements of the force outlet were manufactured using standard machine tools. Design considerations and special attention during machining of the laminated components were successful in guaranteeing component integrity. Chemical etching eliminated electrical shorts resulting between the laminations on the machined surface. Wire erosion was found to result in clean surfaces that do not require further processing but is costly and time-consuming. The permanent magnet rings consist of several trapezoidal segments that were generated out of raw material sheets before being magnetised. Wire erosion and diamond saw cuttings were required to process the hard and brittle material. The magnets and machined surfaces of the magnetic circuit components were finally coated to protect against corrosion.

The cylindrical form of the magnetic circuit lent itself to using a commercially available cast aluminium motor housing with its benefits of lightweight construction, cooling fins and low cost. A shrink fit guarantees an effective thermal bond between the magnetic circuit and the passively cooled aluminium housing. The result is shown in Fig. 4.

Experimental actuator evaluation

The first of the three magnetostrictive actuator versions was characterised dynamically under mechanically free and clamped conditions in an experimental evaluation system presented recently [4] for frequencies in the interval 50–400 Hz. The actuator current and voltage were supplied by a Techron 7700 power supply. The actuator displacement was measured with an eddy current displacement sensor (multiNCDT series 300, micro-epsilon messtechnik) at a fixed position relative to the moving actuator force outlet. The dynamic force was obtained using a piezoelectric force transducer with a nominal dynamic force of 35 kN. The data acquisition was performed with the help of a hardware and software package (dSPACE) installed in a PC. The experimental evaluation system is schematically shown in Fig. 5.

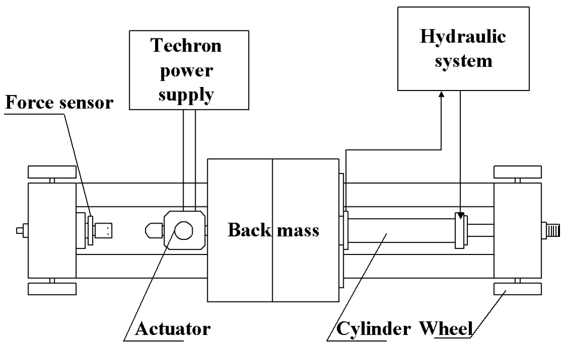

Fig. 5: *Experimental evaluation system.*

The actuator free displacement was measured as a function of current for frequencies up to 400 Hz. The results are depicted in Fig. 6. The actuator displacement is given in units of millistrain ($=\Delta l/l \cdot 10^3$), where Δl is the absolute actuator displacement and l is the length of the active material.

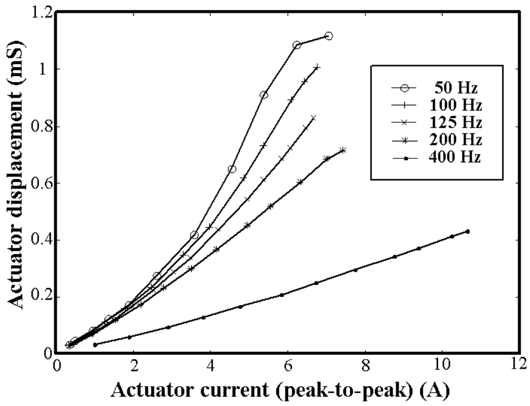

Fig. 6*: Frequency behaviour of the specific actuator displacement (in millistrain) under mechanically free conditions.*

The actuator peak-to-peak displacement reaches 1 millistrain, or an absolute value of 50 µm, for a peak-to-peak current of about 7 A at 100 Hz. This result fulfils the design specification for displacement. For any given value of excitation current, the displacement decreases with increasing frequency. At 400 Hz, a current of 11 A peak-to-peak must be supplied to the actuator to reach a specific displacement of about 0.5 millistrain.

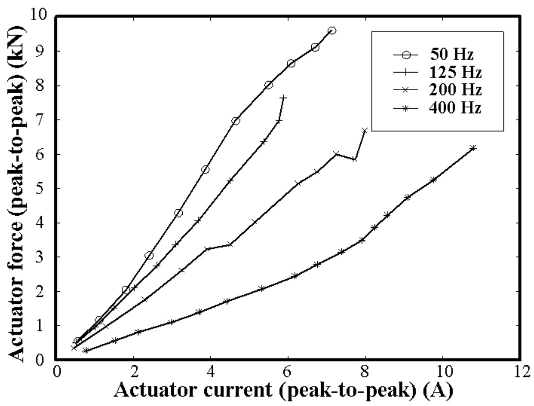

Fig. 7*: Actuator force under mechanically clamped conditions.*

The actuator forces are shown in Fig. 7 for various frequencies up to 400 Hz. A peak-to-peak force of almost 10 kN is reached at 50 Hz for a current of about 8 A peak-to-peak. By extrapolation, the data curves appear to approach the design specification for force. At 400 Hz the peak-to-peak actuator force reduces to around 6 kN for a peak-to-peak current of 11 A.

The reduction of free displacement and blocked force with increased frequency can be attributed to eddy current losses, the majority of which presumably occur in the solid active Terfenol-D rod. Lamination of the active material should further reduce eddy current losses, thereby increasing the dynamic performance of the actuator.

Summary and conclusion

The design, manufacturing and experimental evaluation of a magnetostrictive actuator for vibration control and damage analysis have been presented. Special attention has been given to the design of a powerful, low weight, low cost actuator incorporating several new design and manufacturing features. An optimised actuator concept has been presented, where a new force outlet design presented previously was incorporated for the first time. A highly homogeneous magnetic bias was achieved in the active material while simultaneously reducing the size and weight of the magnetic circuit. Innovative manufacture contributed to the improvement of the mechanical construction and weight reduction of the actuator at reduced cost. The magnetostrictive actuator was tested under realistic operating conditions using a new experimental evaluation system. A displacement of 50 µm was achieved under mechanically free conditions at 100 Hz, 7 A peak-to-peak. The maximum force at 50 Hz was about 10 kN peak-to-peak. Therefore, the actuator fulfilled the displacement and force requirements derived from applications of vibration control and damage analysis on aeronautic and civil structures.

Acknowledgment

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