A Linear SMA Motor as Direct-Drive Robotic Actuator

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ABSTRACT

In this paper a push-pull actuator for commanding the motion of the interphalangeal joints of anthropomorphic robotic hands is proposed. The actuator, based on Shape Memory Alloys (SMA) coil springs, is compact enough to be easily incorporated into the phalangeal structure of a robotic finger, thus eliminating the complex routing of the cables and tendons usually adopted for transmitting motion from conventional actuators (e.g. d.c. servomotors) to the joints.

The performance of the SMA actuator are illustrated, and the concepts of temperature, strain and stress limits for the control of the whole push-pull actuating system are emphasized. The methods adopted to improve the usually limited frequency response of SMA actuators are also described. Finally, the control of the whole system, and some experimental results demonstrating promising actuator performance are illustrated.

1. INTRODUCTION

Appropriate actuators are essential to obtain practical dexterous robotic end-effectors [1]. Geometrical features, mechanical preformance and easy control are among the critical aspects to be considered in the design of an actuator system for anthropomorphic hands. In this context, the need for compact and lightweight actuators, which could be positioned inside the phalanges of the robotic fingers in order to avoid the problems of transmission complexity tied with the use of passive mechanical tendons, is now increasingly recognized.

Several new technologies for robotic actuators have been presented in the recent past: electrostatic motors [2], piezoelectric motors [3], contractile polymers [4] are particularly promising, especially for those applications involving high degree of miniaturization. These technologies, however, do not seem immediately appliable to the actuation of articulated end-effectors.

We have elected to investigate Shape Memory Alloys (SMA) as active elements of robotics actuators, both for their intrinsic attractive properties, and because their technology is developed enough to be already usable.

The Shape Memory Effect (SME), that originates from the thermoelastic martensitic transformation, is at the basis of SMA behavior. The crystallographic and thermodynamic aspects of the thermoelastic martensitic transformation are reviewed in [5], while the thermomechanical characteristics of SMA are described in [6].

Although the few papers presented so far in the scientific literature on SMA - based robotic actuators have not solved yet the issue of their practical validity and reliability, research on the mechanical performance of SMA materials has confirmed some peculiar advantages of this technology with respect to conventional robotic actuators. For example, size and weight of SMA active elements are low in absolute, and the recovering force per unit wieght is very large compared with other types of conventional actuators [7]. An additional advantage of SMA actuators is their intrinsic simplicity. In fact, typical SMA actuator can consist just of a wire, or spring, or ribbon of SMA material, and two leads, being the heating process of SMA commonly obtained by using Joule heat generated by an electric current.

At present few papers on SMA actuators for robotic applications have been presented. Hirose et al. [8] proposed a particular configuration, called ξ-array, of the active elements inside an actuating device. They connected electrically in series all the active SMA elements, configured as coil springs. The SMA elements worked mechanically in parallel against a movable piston. A distinctive feature of the ξ-array configuration is that of providing higher electric resistance of the active elements, thus reducing the energy loss and heating of the lead wires. The ξ-array configuration also allows driving the SMA elements with high voltage, low current electric power sources.

The ξ-array configuration for SMA actuators has been also utilized by Ikuta et al. [9] for the development of a SMA servo actuator system with electric resistance feedback control, implemented in an active endoscope. This technique is based on the fact that the electric resistance of the SMA, which varies with the percentage of austenite in the alloy (and therefore with temperature) can be easily measured in an ξ-array configuration.

A paper by Hashimoto at al. [10] addresses another important aspect of the design of SMA actuators, i.e. the role of the cooling phase of a SMA module when antagonistic type actuators are used. When heated, SMA respond very fast: they shrink, by recovering their original shape, with a velocity that depends on the input power (Hashimoto obtained, for a TiNi wire of 1.0 mm of diameter, length of 200 mm and for no load, a velocity of 0.03 m/s for an input power of about 200 W).

On the other hand, the response of the actuator is slow on cooling. The cooling rate is proportional to the ratio of the surface area of the active element to the heat capacity. Furthermore, it depends strongly on the cooling method. Hashimoto reported the cooling curves of a 0.8 mm diameter TiNi wire, for various cooling

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methods (air cooling, ventilation, water cooling and heat-sink), showing that the best performance are achieved with heat-sink (cooling rate: 21 °C/s). In fact, Hashimoto utilized this cooling method for a bias type actuator (i.e. with an active SMA element and a bias spring) for a leg of a biped robot. The application of a heat-sink cooling was possible for this application because the active element was a SMA wire. For other active element configurations, such as a simple coil spring, the application of a heat-sink cooling method poses severe design problems.

K. Kuribayashi in [7] has proposed a SMA actuator composed of two NiTi alloy wires. He developed a mathematical model of both the actuator and control systems and proved the validity of the model with experimental tests.

Until now, however, the more complete SMA actuator system described in the literature is probably the one developed by Nakano et al. [11] for commanding the motion of the interphalangeal joints and wrist of the Hitachi's robot hand. The active elements are SMA wires of small diameter (0.2 mm for the fingers and 0.35 mm for the wrist), providing an angular velocity of 90 degrees/s.

Our work on SMA is not directed just to obtain a prototype of SMA robotic actuator, but rather to acquire expertise and knowledge on the material in order to fully exploit its potential properties.

Based on this approach, we have identified two broad large consecutive research domains aimed at, respectively: i) establishing a useful set of tests capable of predicting the thermomechanical behavior of SMA active elements and ii) analyzing all the aspects inherently associated with the realization of a practical actuator system.

This paper poses emphasis both on the experimental tests on the alloy and on the design of components capable of protecting the active elements of the actuator against external overload, as it is especially necessary when SMA is in the austenite phase. Based on this analysis, we have incorporated a mechanical protection device in series with the active elements of the actuator. Another important aspect we have taken into account during the actuator design phase refers to the cooling method of the active elements: a water cooling system has been implemented in the experimental setup. The command and the control procedures for the actuator are also described. Finally, results of tests on the behavior of the actuator for various input signal frequencies are presented.

2. MATERIALS AND METHOD

2.1. Material Characterization

The SMA material we have used is a Nitinol wire, 0.5 mm diameter (Innovative Technologies International, Beltsville, MD, U.S.A.). The thermomechanical behavior of the SMA wire has been determined by isometric, isotonic and isothermal tests. Based on these data, we introduced the concept of "Limit Curves", which have a fundamental role in the successive actuator design phase. The thermomechanical behavior of the SMA material can be represented in the 3-D space (σ , ε , τ) and each functioning status can be indicated as a point **p** belonging to a surface S. This surface S is obtained by enveloping, for example all the stress-strain curves obtained at different temperatures. An explicative example of the "flow stress-strain-temperature surface" is presented in [6]. The "Limit Curves" are the projections on the coordinate planes P1 = (ε , τ), P2 = (ε , σ) and P3 = (σ , τ) of the "General Limit Curve" in the 3-D space that limits the SME behavior of the material. The meaning of the General Limit Curve can be understood by considering that curve in the 3-D space as a bound for the working path, belonging to the flow stress-strain temperature surface, which represents the successive status positions of the alloy. If the working path passes across the General Limit Curve, the SMA material will loose its SME and shape recovery will be incomplete. For this reason the knowledge of the General Limit Curve is essential to accurately predict the performance of the active element of the SMA actuator system.

The three projections on the planes P1 = (ε , τ), P2 = (ε , σ) and P3 = (σ , τ) of the General Limit Curve for the SMA material are represented in Fig. 1.

Fig. 1 (b) represents the course of the maximum reversion stress obtainable versus the initial deformaton of the SMA sample. From this curve two important parameters expressing the active element performance can be extracted : i) the maximum deformation obtainable from the material at low temperature and ii) the stress relative to the apparent yield stress of the austenite at high temperature.

2.2. The SMA active elements

A 0.5 mm diameter SMA wire has been used for the realization of the active elements of the actuator. The first issue to consider in the design of the active elements is the appropriate geometry for obtaining the desired actuator performance.

It is desirable to obtain the highest strength and compliance, for the same total volume of the SMA element. A mechanical spring is a practical example of a structure specialized in high deformation and possessing, at the same time, small volume and high strength. For this reason we selected the geometry of a coil (helicoidal) spring axially loaded for the SMA active elements. More importance has been attributed to the compliance than to the force exerted by the active element. In fact, a simple SMA wire could exert a larger reversion force but, compared with a SMA spring having the same axial dimensions, the deformation would result considerably smaller. An acceptable compromise between force and deformation has been obtained with a SMA coil spring having a small (1.5 mm) diameter, a length of 7.0 mm and composed by 14 coils; each spring weights only 0.08 g.

The characterization of the active element performance has been carried out by following the same procedures outlined in the case of the wire. Isometric and isotonic tests have been performed also for the coil springs. The results of these experimental tests are reported in Fig. 2.

The most important parameters derived from the experimental data on the coil spring are the limit axial displacement at low temperature (i.e. the point where a damage occurs when the material is completely in the martensitic phase) and the force exerted at the yield point (when the material is completely in the austenite phase, at the limit of the thermodynamic stability of austenite).

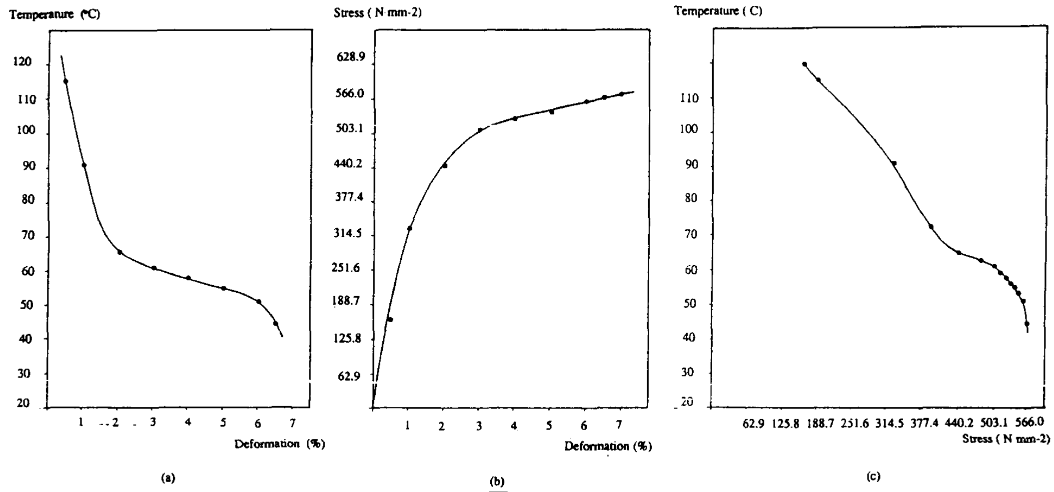

Fig. 1 Limit Curves, obtained experimentally, indicating the thermomechanical behavior of the SMA wire (diameter 0.5 mm) used for the realization of the active elements of the actuator.

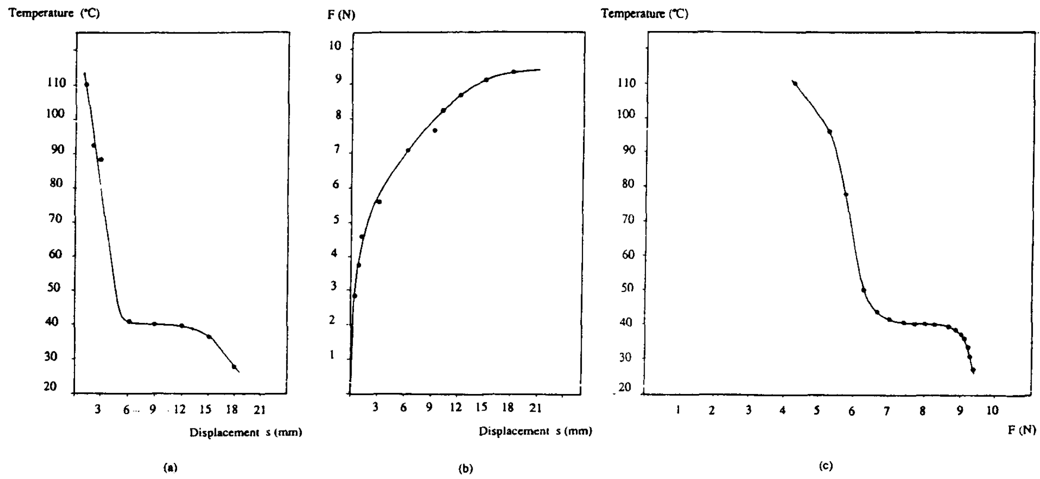

Fig. 2 Results of the experimental tests performed on the SMA coil springs: Limit Curves.

2.3. Design considerations for the SMA actuator

Consider the problem of moving a robotic finger joint with a SMA active element: the need arises of applying a desired force to the active element, at low temperature, in order to deform it. The resulting deformation will be recovered by heating the active element. The initial force, at low temperature and in absence of an external trorque applied to the joint, should be sufficiently high to rapidly deform the active element. Instead the force should decrease to zero, at high temperature, when the active element shrinks to its original undeformed shape. This requirement can be satisfied by using either a bias spring (obtaining a bias type actuator configuaration [7]) or another SMA active element (antagonistic or push-pull configuaration [7]), in antagonistic configuration with the active element. We focused our attention on the design of a SMA agonistic-antagonistic configuration because it allows more accurate control in both directions. The scheme of the complete experimental actuator system is depicted in Fig. 3.

Two SMA active elements are contained inside a small aluminum box where a constant flow of distilled water is mantained during the operation in order to cool the two SMA coil springs. The water cooling method has been used because it is efficient and also because it could be easily adopted in the case the actuator is inserted inside a robotic finger.

An extra-load protection device, realized with a preloaded passive steel spring, is disposed in series with each SMA active element. The protection is calibrated in order to operate against external loads of magnitude

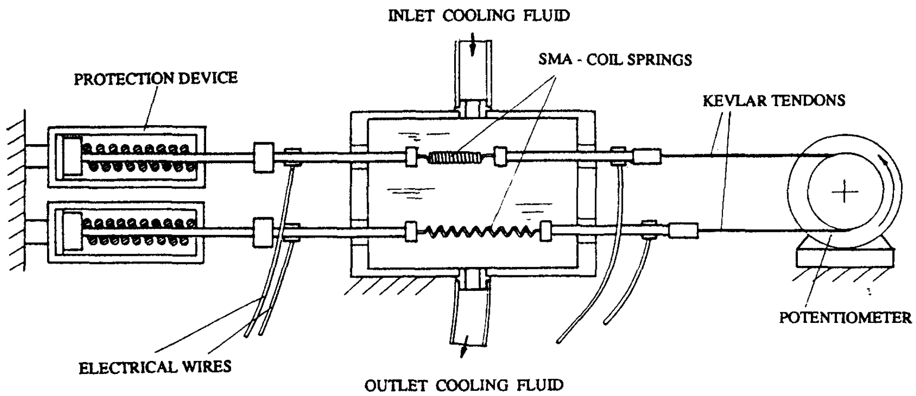

Fig. 3 Scheme of the experimental SMA actuator system.

greater than a certain value F , defined as protection threshold. The determination of the optimum value for F depends not only from the yield point of the material at the austenite phase (at high temperature) but also from the effective linear displacement performed by the active element. Given a push-pull configuration of the SMA actuator, its maximum absolute displacement can be evaluated by considering the isotonic curve of the active element correspondent to a load equal to the protection threshold. The difference between the displacement at low temperature and that at high temperature, calculated from the isotonic curve, gives the maximum actuator displacement.

From the isotonic curves for a SMA spring (see Fig. 4), we note that, for a limited interval of temperature, there is a considerably large deformation of the SMA element between the two consecutive knees of each curve.

This is the region of most convenient working conditions, i.e. a further increase in temperature out of this range does not imply a significant increase in the deformation range. The difference between the two boundary limits of the deformation range can be viewed as the maximum stroke an active element can practically perform.

On the basis of the above consideration, the best value for the protection threshold F_o is that of the isotonic curve intersecting the Limit Curve $P1 = (\varepsilon, \tau)$ in correspondence of its upper knee. In this way, if now the Limit Curve $P3 = (\sigma, \tau)$ is considered, the protection system limits both the axial load acting on the active element to the value of F_o , and the temperature of the material to the corresponding value T_o . The desired value of the axial force on the SMA spring is obtained by introducing, in series, the protection device calibrated to the value of the threshold F_o , whereas the limit of T_o is obtained by an appropriate calibration of the maximum output current supplied by the drivers. The introduction of a protection device increases the repeatability performance of the whole actuation system.

Owing to the presence of the protection device, the real working area in the plane $P3 = (\sigma, \tau)$ results only a portion of the working area theoretically available. The actual working area is shown (shaded) in Fig. 5.

The reliable behavior of the active element is obtained automatically by operating inside the Limit Domain represented in Fig. 5; moreover, temperature control is not required because the drivers have been already calibrated, at the maximum power, for the temperature T_o .

Another important aspect of the design of a SMA actuator refers to the control system. For the experimental system presented in Fig. 3, we have used a pure position control. The control variable is the angular rotation of the joint. The value of the angular rotation is measured by a potentiometer positioned on the same axis of a pulley to which Kevlar tendons transmit the motion generated by the SMA active elements. The scheme of the control system is depicted in Fig. 6.

The output of the two drivers, which are voltage-driven ideal current generators, is a current. This provides large flexibility to the whole control system.

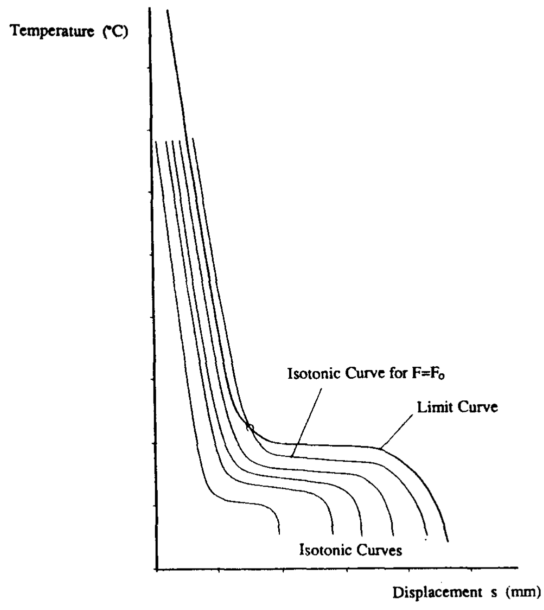

Fig. 4 Isotonic curves and Limit Curve in the plane $P = (s, T)$.

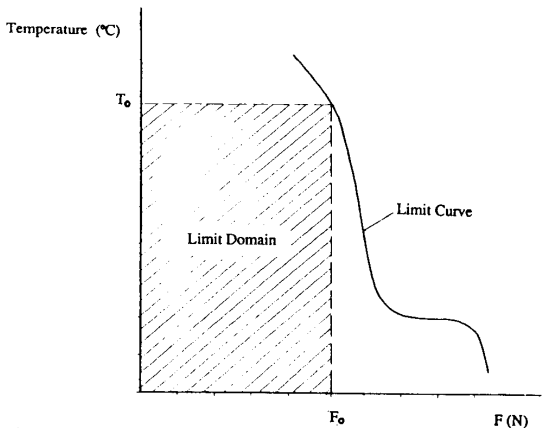

Fig. 5 The Limit Domain (shaded region comprised between the lines $F=F_o$ and $T=T_o$) restricts the working area of the SMA active element but allows the actuator to operate in safety conditions.

In fact, the time constants of the whole control system (control logic plus power system) do not change even if the length of the active element varies, provided that the transverse geometry and the cooling conditions remain constant. The control logic compares the input signal with the value of the angular position read by the potentiometer. The signal error processing is implemented by a P.I. block. The reset occurs when the signal error changes in sign.

3. RESULTS

The experimental SMA actuator system described in the previous section has been tested in order to demonstrate the validity of our theoretical assumptions.

Experimental tests have been carried out in order to obtain the response of the actuator system to sinusoidal input. The initial conditions of the system were the following: a) the force F_o for the mechanical protection was set equal to 5.0 N; b) the two SMA active elements were initially deformed in order to reach the maximum linear actuator displacement; c) a sinusoidal input was set, whose amplitude was calculated during the calibration procedure (when the contraction of the SMA springs was commanded in quasi-static conditions).

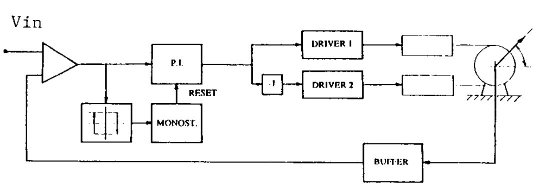

Fig. 6 Scheme of the control system of the SMA actuator.

An example of the curves recorded during the experimental tests is shown in Fig. 7.

Experimental results report the four traces relative to: a) the input currents for the two active elements; b) the input voltage signal and c) the output of the angular position as recorded by the potentiometer. In particular, Figure 7 shows all these curves for a frequency comprises from 0.9 to 1.0 Hz. However, tests have been performed also by varying the input frequency from 1.0 to 10.0 Hz. The frequency response plot is reported in Fig. 8.

The frequency cut-off of the actuator system is between 1.0 and 2.0 Hz. A total linearized displacement of the joint equal to 7.0 mm has been achieved at 1 Hz. These results are quite encouraging for the validity of the whole system design. In particular it is worth observing that the introduction of the cooling and protection systems has played an essential role in obtaining such a high frequency cut-off.

4. DISCUSSION

An experimental SMA actuator has been presented. The study of the actuator has been performed by analyzing first the thermomechanical behavior of the material. The characterization phase has been approached by evaluating experimentally the behavior of the SMA in several working conditions (isometric, isotonic and isothermal tests). As a result of the tests performed on the material, the concept of Limit Curve has been introduced. The Limit Curves define the boundary working conditions of the material, a fundamental information for a successfull design of a SMA actuator system.

Particular attention has been devoted to analyze the problems of the cooling of the SMA active elements (solved by a water cooling method), and of the protection of the active elements against external overloads (with the consequent permanent loose of SME).

Experimental tests on the actuator system have been performed and results to sinusoidal input excitation have been reported for various input signal frequencies.

The most significant result we obtained relates to the frequency cut-off value comprised between 1.0 and 2.0 Hz, a value much higher than the previous values reported with similar push-pull configurations [12][13].

General conclusive results can be summarized as follows: i) the frequency response obtained with this experimental SMA actuator configuration can be considered as complying with the requirements of the actuator systems for robotic end-effectors for fine manipulative tasks. Such high frequency cut-off is due to the fluid (in our case water) cooling system, a solution that has also the merit of being technologically easy to realize, even if a high degree of miniaturizatin is required; ii) the experimental data on the active elements performances (for the coil spring considered in our experiments the force exerted was about 9.0 N with an axial displacement of 22 mm) and the theoretical data extracted by the scientific literature are in good agreement; furthermore, knowledge of the material, oriented to practical application, has been achieved during the material characterization phase; iii) SMA technology allows to realize compact and lightweight actuators. Although the experimental SMA actuator presented here has not

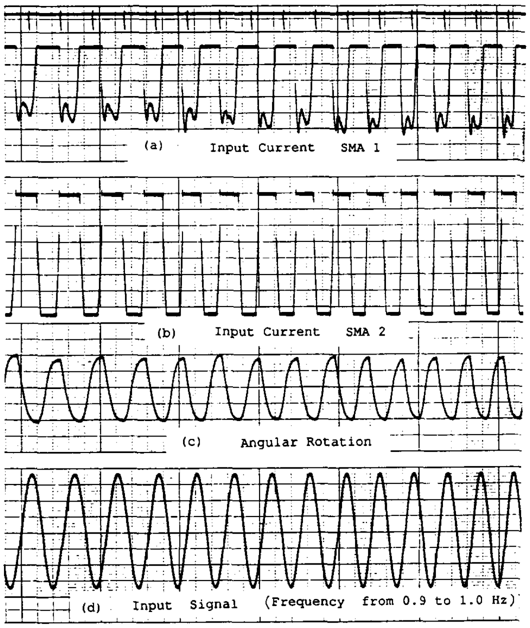

Fig. 7 Results of the experimental tests on the SMA actuator system. The significance of the four curves is: a) and b) courses of the two input currents in the two SMA active elements; c) output signal relative to the angular position as recorded by the potentiometer; d) inpout signal of determined amplitude and frequency.

been realized for incorporation in robotic fingers, but just for testing the efficiency of some design solutions; results encourage the development of a scaled miniaturized version we have already designed for the direct application to a robotic finger joint; iv) a computer synthetized control as well as a force control are under investigation.

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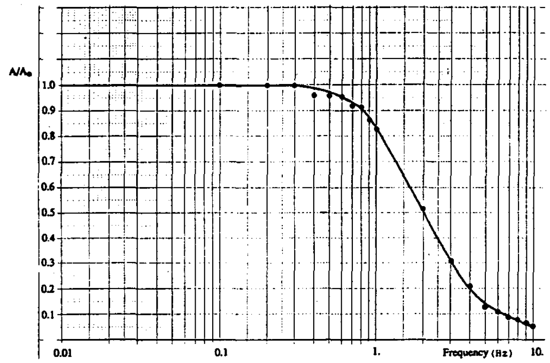

Fig. 8 The frequency response plot for the SMA actuator system.

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