Sensors and Actuators A 165 (2011) 342–350

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A model of magnetostrictive actuators for active vibration control

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ARTICLE INFO

Article history:
Received 23 March 2010
Received in revised form 19 October 2010
Accepted 31 October 2010
Available online 9 November 2010

Keywords:
Magnetostrictive actuator
Terfenol-D
Magnetostriction
Active vibration control

ABSTRACT

One of the most frequent applications of magnetostrictive actuator technology is the active structural vibration control (AVC). Magnetostrictive actuators (MAs) can deliver high-output forces and can be driven at high frequencies. These characteristics make them suitable for a variety of vibration control applications. The use of this technology, however, requires an accurate knowledge of the dynamics of such actuators. Several models are available in the literature. However, their use in control applications, characterized by high dynamics, is often limited by nonlinearities and complexity of the model. To overcome this difficulty, the paper introduces a linear model of magnetostrictive actuators that is valid in a range of frequencies below 2 kHz. The assumptions supporting the linearity of the system are discussed and the theoretical model is presented. Finally the model is validated through experimental tests carried out on two different magnetostrictive actuators.

1. Introduction

Undesirable vibrations can induce noise, bad performance or even severe damage. Passive damping materials have been used effectively for a very long time but in many cases, especially for small amplitude and low frequency vibration, passive damping materials are inadequate and not effective [1,2]. Hence active vibration control (AVC) techniques with feedback control have begun to be used to meet performance requirements. With the development of "smart" materials, the corresponding actuators for active vibration control have been the focus of research for years. In this context, magnetostrictive devices are considered one of the most interesting opportunity in active vibration control actuators technology beside piezoelectric, shape memory and magnetorheological actuators [3]. Magnetostrictive actuators deliver high-output forces and relatively high displacements (compared to other emerging actuator technologies). Moreover, they can be driven at high frequencies. These characteristics make them suitable for a variety of vibration control applications such as vibrations control of machine tools [1], of ship structures [2], of helicopter blades [3], of airplanes [4], of cylindrical [5] and linear [6] structures, of cables [7] and multi-dof systems [8].

The effective use of magnetostrictive actuators requires an accurate knowledge of the device dynamics as well as a mathematical model to implement control strategies.

The effect of magnetostriction, which is the basis of the operating principle of these actuators [9], is very complex due to the interactions of electrical, magnetic and mechanical phenomena. This complexity is compounded by the non-linear behavior of the material (generally Terfenol-D [11,12] or Galfenol [13]) observed at high operating frequencies [10]. In particular, the behavior of Terfernol-D has been investigated at various operating conditions [14] and for different thickness [15].

Currently, there are several models in the literature describing magnetostriction. Many works focus on the modeling of the hysteresis of the magnetostrictive material following two approaches: physics-based and phenomenon-based hysteresis models [16]. Since physics-based hysteresis models are usually derived from basic physical assumptions, they allow to obtain a clear physical insight and explanation of the phenomenon they deal with. The drawback is that they require substantial physics knowledge and are specific to particular systems thus, they are not as common as phenomenon-based models. Jiles–Atherton model of ferromagnetic hysteresis is one of the most well known physics-based hysteresis models [17–19]. It is a quantitative model that is based on a macromagnetic formulation. The model describes isotropic polycrystalline materials with domain wall motion as the main magnetization process.

On the contrary, phenomenon-based models do not provide insight into the behavior of the material, but are commonly used when material behavior is not the main focus. Among them, Presaich model [20–22] and Prandtl–Ishlinskii model [23] are application independent and can describe or predict the hysteretic behavior of a consistent and well-controlled material very well. Recent works deals with the development of complex numerical

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doi:10.1016/j.sna.2010.10.019

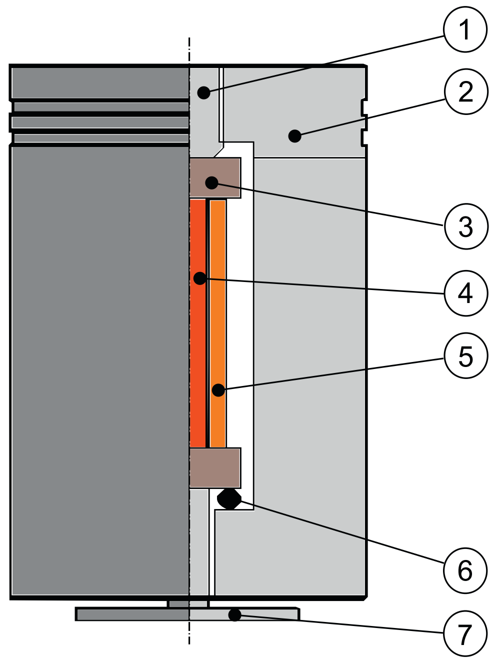

Fig. 1. Section of a linear inertial magnetostrictive actuator: (1) prestressing screw, (2) inertial mass, (3) permanent magnets, (4) magnetostrictive rod, (5) coil, (6) spring and (7) end effector.

method such as neural networks [24] or genetic algorithms [25] to identify hysteresis parameters.

Although there are several models in the literature, their practical use in control applications is often limited by their nonlinearities and complexity.

It should be recalled, in fact, that traditional control theory is based on linear time invariant systems. Thus a too detailed knowledge of the dynamic behavior of the system is not only not required, but it can also prevent the design of classical controllers such as PID controllers. Moreover, for real-time applications, the complexity of the model may lead to tough hardware measurements (and thus high costs) without leading to any appreciable improvement in performance. Accordingly, the aim of this work is to set-up the simplest model of a magnetostrictive actuators that can be profitably used in these applications.

2. Modeling inertial magnetostrictive actuators

2.1. Functioning principle of magnetostrictive inertial actuators

A typical magnetostrictive actuator is shown in Fig. 1. The active element is a giant magnetostrictive rod which is surrounded by a coil and is subjected to a magnetic field generated by permanent magnets placed at the ends of the bar. When the supplied current flows in the coil, a variation of the electric field that passes through the magnetostrictive material produces a change in the magnetic field opposing this variation. This leads to the subsequent alignment of the magnetic domains of the material and thus to the lengthening/shortening of the magnetostrictive rod and to the generation of a high force. A prestress mechanism (generally a screw) compresses the magnetostrictive rod pushing it on an elastic element. The requirement of the active material to be mechanically compressed during operation is twofold. The tensile strength of the material is limited (≈28 MPa) and the efficiency and coupling factors are considerably higher under compression. Normally the elastic element has a low stiffness. Since the magnetostrictive rod and the elastic element are in parallel, the prestress mechanism does not appreciably affect the total effective stiffness.

Table 1
Main characteristics of Terfenol-D and Galfenol.

	Terfenol-D $Tb_{0.3}Dy_{0.7}Fe_2$	Galfenol FeGa
$s^H/10^{-11}$ [m²/N]	3.3–4.5 (4.5)	3.1
$d/10^{-8}$ [m/A]	2.0–2.1 (2.1)	3.4–4.2
μ^T/μ^0	12	290

2.2. Magnetomechanical coupling equations

The behavior of magnetostrictive materials is nonlinear but, under suitable conditions, it can be approximated as linear. The main assumptions are:

- low working frequencies,
- reversible magnetostriction processes (no power losses),
- stress and strain distribution uniform throughout the magnetostrictive rod.

Under these assumptions the coupling between the mechanical strain and the magnetization of the material is represented by the linear magnetomechanical equations [11]:

$$S = s^H T + dH \tag{1}$$

$$B = d^* T + \mu^T H \tag{2}$$

S being the strain, T the stress, s^H the mechanical compliance at constant applied magnetic-field strength H, d and d^* the linear piezomagnetic cross-coupling coefficients, μ^T the magnetic permeability at a constant stress, and B the magnetic-flux within the material. If the magnetostrictive process is assumed to be reversible, then $d^* = d$. This would be normally true for low-level driving forces or fields.

The most common magnetostrictive materials are Terfenol-D [11] and Galfenol [13]. Table 1 sums up the main features of these two materials. Values in brackets coincide with the ones used in the mathematical model described below.

2.3. The linear model

The force F_{mag} exerted by the magnetostrictive rod is

$$F_{mag} = TA \tag{3}$$

where A is the cross-section area of the magnetostrictive rod. The exerted force is a function of the strain S and the supplied current I. To highlight these dependences, Eq. (1) can be rewritten as

$$T = \frac{-S + dH}{s^H} \tag{4}$$

The current flowing in the coil windings and generating the magnetic field H can be calculated through the circuitation of the magnetic field itself

$$H = \frac{n}{\delta \cdot l} I \tag{5}$$

where n is the number of the winding turns and l is the length of the magnetostrictive bar. Coefficient δ has been introduced to calculate the length of the magnetic field lines to perform the circuitation.

Since the magnetic field is constrained to flow inside the ferromagnetic material, due to the shape of the actuator, $\delta \approx 2$ (i.e. the length of magnetic field lines is 2 times the length of the magnetostrictive rod).

The actual length of the magnetostrictive rod is equal to

$$l = L + x \tag{6}$$