Rectilinear Dynamics of Magnetically Driven Microsystems

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ABSTRACT

The dynamic behavior of magnetically driven microsystems is investigated in this study. An experimental setup designed to simulate the dynamic response of a micro-roller element moving in rectilinear path under influence of an external magnetic field is presented. Results of element response to step excitation field are discussed and an analytical model for the response based on a lumped capacitance model is proposed. A computer simulation of the proposed model was also conducted and the results of dynamic response to step input were compared with those obtained experimentally.

Keywords: *Microelectromechanical systems. Magnetically driven systems.*

INTRODUCTION

Magnetically Driven Microsystems (MDM) utilize the force generated by an external magnetic field to actuate a dynamic motion of a microelement or a microsystem [1]. In these systems, a moving magnetic field or a magnetic field with varying intensity is utilized to actively control the movement of a magnetically actuatable microelement embedded within the structure of the microsystem. Recent advances in creating materials having strong magnet [2] accompanied by advances in microsystems design and manufacture [3] make the concept of MDM both technologically feasible and economically attractive.

The main advantage of using MDM concept in practical application is the elimination of the bulky electric circuitry that is required in the torque generation microactuators. MDM is a clean, noninvasive, wireless and can be produced and maintained at practical cost. Additionally, with optimum microelement design, magnetically driven microactuators can provide higher torque than that is possible from the electrical microactuators.

This study investigates an experimental and a mathematical model of the rectilinear motion dynamics of MDM. A scaled-up experiment was designed to simulate the dynamic response of a magnetically driven micro-roller constrained to rectilinear motion. A lumped capacitance model is used to describe the magnetic actuation of a microelement to the external field. The dynamic response of the magnetic material is modeled by a spring-mass-damper analogy. The model of a magnetically actuated microelement constrained to rectilinear motion was simulated by the *Working Model*ä motion simulations code. Dynamic response of the microelement to step excitation field was obtained. Results obtained from computer simulation were used to describe the proposed mathematical model.

EXPERIMENTAL SETUP

A scaled-up experiment designed to study the dynamic response of a magnetically driven micro-roller element is shown in Figure 1. In this experiment, a 12 mm diameter magnetically actuatable macro-roller element (A) is used as scaled models for a microelement which can have a size down to 10 μm. Magnetic field from a Neodymium-Iron-Boron permanent magnets (B) with a magnetic field strength of 1.5 Tesla was used to excite the macro-roller. The macro-roller in this setup rolls without sliding on a Plexiglas flat plate (C) under the influence of the magnetic field. The flat plate has a thickness of 3 mm and two permanent magnetic columns are placed beneath it. The orientations of the magnetic poles are shown in the figure with one magnetic north pole and one magnetic south pole facing the plate (C). The macro-roller is made of ferromagnetic material (iron) and placed initially symmetrical to the magnetic column at a distance (D) from the magnets.

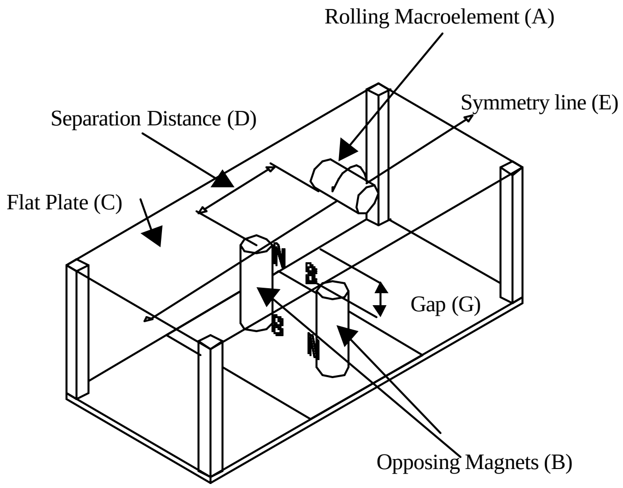

Figure 1. A Schematic of the experimental setup

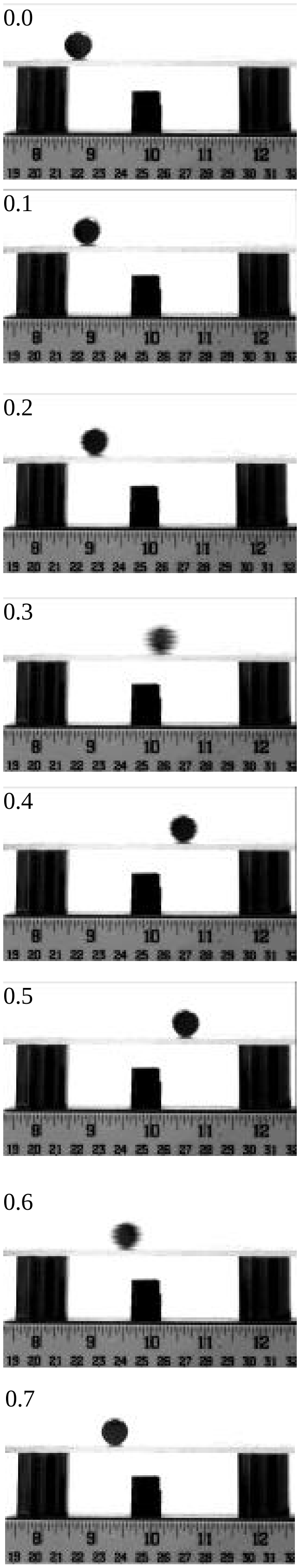

Figure 2. Macro-element response to step excitation. Images taken during the first period of response.

Dynamic response of the macro-roller is recorded using a digital video camera equipped with a data acquisition and image capturing hardware with a capture speed of up to 20 frames per second. Resulting images could then be analyzed using the *ImageTool* ä image analysis software.

At the commence of the experiment, the macro-roller is released from the holder (not shown) and allowed to move on the surface (C) along the symmetry line (E), first toward the magnets. Depending on the dynamic parameters such as mass of the roller, magnetic field strength, initial separation distance, and gap between the magnets (B) and the surface (C), the micro-roller may or may not execute an oscillatory motion.

In this study, macro-roller (A) had a mass of 25 g. and was allowed to roll freely along the flat surface (B). The initial separation distance (D) was 30 mm and the gap (G) was 10 mm. Dynamic response of the micro-roller was recorded with a capture speed of 10 frames per second. Figure 2. shows a set of consecutive images obtained from the actual experiment.

Figure 3 shows the position the center point of the roller as a fucntion of time. The results show a periodic motion with a decaying amplitude. The period of oscillation starts at approximately 0.7 second and decreases to 0.4 second after 6 or 7 cycles.

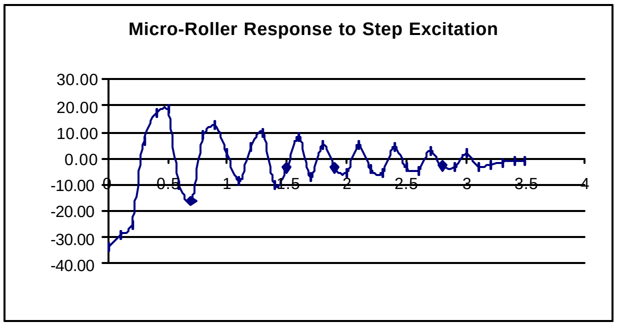

Figure 3. Micro-roller response to step excitation

ANALYTICAL MODEL

Figure 4 shows a projected view of a magnetically driven micro-roller element constrained to rectilinear motion under the influence of a magnetic field. Microelement (A) rolls along the straight horizontal plate (B). The external magnetic field is created by a permanent magnet (B). The differential equation that governs the distance (x) between the microelement (A) and the magnet (B) is:

$$m\ddot{x} = f_{me}(x, \dot{x}) \qquad (1)$$

where,

m is the microelement mass
x, $\dot{x}$ and $\ddot{x}$ are microelement position, velocity and acceleration, respectively.

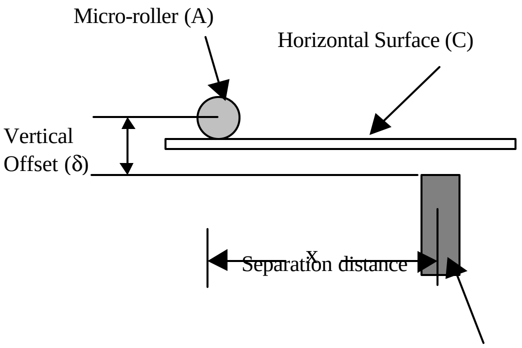

Figure 4. Rectilinear motion of a micro-roller element

The interaction force $f_{me}(x, \dot{x})$ between the microelement and the magnetic field is a function of both the position, x, and the velocity, $\dot{x}$, of the microelement. Physically, the interaction force f_{me} falls off with the inverse square relationship to the distance, x, from the magnet. The dependence of the interaction force on velocity is complicated and depends on the dissipation effects resulting from microscopic reorientation of magnetic dipoles within the atoms of the material when exposed to magnetic field as well as the general dynamics characteristics of the system. Thus the interaction force can be modelled as:

$$f_{me}(x, \dot{x}) = \frac{-Kx}{(x^2 + \boldsymbol{d}^2)^{3/2}} + f_v(\dot{x}) \qquad (2)$$

where δ is the vertical offset between the micro-roller and the permanent magnet, and K is the magnetic interaction coefficient.

COMPUTER SIMULATION

In order to simplify the analytical description of the interaction force between the magnetic microelement and the magnetic field, a localized magnet model is proposed herein. Since the size of the magnetic microelement is very small compared to that of the magnetic field, the force on the microelement is assumed to originate from a localized point located at x distance from the permanent magnet shown in Figure 4.

To account for the dynamic response of the ferromagnetic material to the magnetic field, a lumped capacitance spring-mass-damper analogy is used. An example model that simulates the conditions of the experiment described was created in the *Working Model* ä motion simulation package as shown in Figure 5. In this model a 25 g ferromagnetic roller moving is influenced by an interaction force from a permanent magnet and is allowed to roll freely along a flat surface. Magnetic force between the permanent magnet and the roller is defined as a pairwise force field according to the inverse square law. A rotational spring with a rotational stiffness of 2 N.m and a rotational damper with a damping coefficient of 0.08 N.m.s are defined to counteract the influence of the magnetic moment.

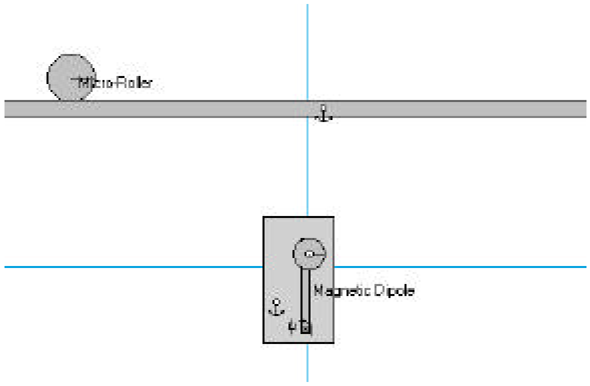

Figure 5. Lumped capacitance model for a ferromagnetic micro-roller moving under the influence of a stationary permanent magnet created in *Working Model.*

Figure 6 shows a sample response of the micro-roller a step excitation. The response is calculated by a Runga-Kutta integration of the system's second order motion equations, which are generated automatically by the software. The simulation shown in Figure 6 gives a similar response to that obtained from experimental measurement and plotted in Figure 3. Figure 6 shows the decaying behavior of the periodic motion with a period of approximately 0.5 seconds. While the details of magnetic forcing function is complex and unknown, the mathematical simulation shows that the dynamic motion of Magnetically Driven Microsystems may be approximately simulated by a second order differential equation.

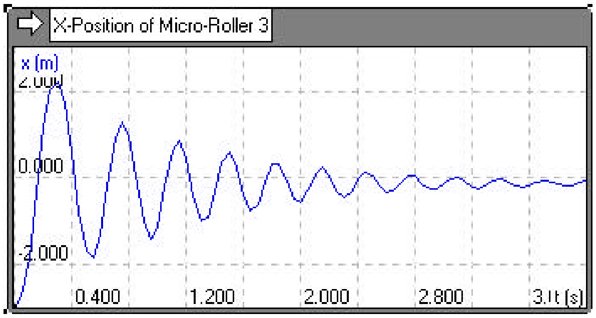

Figure 6. Response of micro-roller to step excitation.

CONCLUSION

The paper presented an experimental investigation and a numerical simulation for the dynamic response of magnetically driven microsystems in rectilinear motion under the influence of an external magnetic field. The dynamic response obtained from the experimental procedure represents an oscillatory motion around an equilibrium point. The lumped capacitance model was used to numerically simulate the observed dynamic response. The model utilizes the spring-mass-damper analogy to model the dynamic response within the magnetic material itself.

A model of a second order differential equation may approximate the response of a magnetically driven microsystem.

Critical parameters affecting the performance of MDM systems in practical applications are identified. The parameters important to MDM motion include a) magnetic field strength and distribution, b) magnetic material of microelement, c) friction and drag in microelement medium, and d) geometry of the system The study suggests a procedure for design of MDM systems with optimum size, weight and performance characteristics.

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