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Review of Capabilities of a Linear Micropositioner Based on a Flexible Mechanism

Análisis sobre las Capacidades de Actuador Micrométrico basado en Elemento Flexible

Investigación

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Resumen

Este artículo presenta el análisis de capacidades de un actuador lineal de resolución micrométrica que puede ser empleado para lograr posicionamiento de la pieza de trabajo en el proceso de micro electroerosión. El actuador fue desarrollado utilizando un elemento flexible accionado por un solenoide, un sistema de control de lazo abierto fue empleado para el posicionamiento. El sistema de control utiliza una computadora personal conectada a un microcontrolador a través del protocolo RS232 y el microcontrolador ejecuta un programa escrito en lenguaje C que interpreta comandos provenientes de la computadora. El sistema varia la fuerza producida por un solenoide utilizando la técnica de modulación de ancho de pulso (PWM por sus siglas en inglés). Las capacidades del actuador fueron evaluadas mediante el desplazamiento de una masa de 1 kg en una distancia de 30μm. La posición del resultante de la masa fue medida utilizando un transformador variable diferencial (LVDT) con una resolución de 0.5μm. Datos experimentales fueron recolectados utilizando un sistema de adquisición de datos desarrollado en el lenguaje de instrumentación LabView. Los resultados muestran que el actuador es capaz de alcanzar una precisión de magnitud similar a la del sistema de medición empleado. Un diseño de experimentos fue realizado para evaluar las capacidades del actuador. El comportamiento de desplazamiento del actuador presenta histéresis debido a su constitución basada en elementos electromagnéticos. El impacto de los parámetros de control sobre la histéresis fue evaluado. Una combinación óptima de parámetros de control es propuesta la cual permite rangos de desplazamiento óptimos y reduce la histéresis.

Palabras clave: Elemento flexible, Solenoide, Microposicionador, Actuador electromagnético, Histéresis.

Abstract

This article presents the development of an actuator for micro electrical discharge machining (μEDM). A lineal micropositioner was developed using a solenoid-flexural element architecture and an open-loop control configuration. The open-loop control system uses a personal computer (PC) connected to a microcontroller through an interface developed on language C and linked to the RS232 protocol. The system varies the force delivered by the solenoid using the technique of pulse width modulation (PWM). The capabilities of the actuator were evaluated by displacing a 1 kg mass over a 30μm lenght. The position of the micropositioner was measured using a linear variable differential transformer (LVDT) with a resolution of 0.5μm. Experimental data was collected by a data acquisition system developed in LabView. The results show that the actuator is capable of archiving accuracies that fall within the limits of uncertainty of the measuring system. A Design of Experiments (DoE) was used to evaluate the micropositioner performance. The displacement behavior of the actuator presents hysteresis due its electromagnetic constitution. The impact of each of the control parameters on the hysteresis behavior of the actuator was evaluated. An optimal control parameter combination that reduces hysteresis and magnifies displacement range is proposed.

Key words: Flexure, Solenoid, Micropositioner, Hysteresis

Introduction

Current conventional manufacturing processes rely mostly on cutting tools to remove material. Examples of this kind of process are turning and milling. A new generation of products requires the manufacture of small components, with dimensions into the meso-micrometer range (1 to 0.001 mm). Micro-electro-mechanical-systems (MEMS) and micro medical devices that are inserted into the human body are examples of microproducts in use today. Conventional large scale machines are not suitable for the manufacturing of those parts, because they consume excessive energy, space and material when applied to these sizes [1]. As a result, new manufacturing processes have evolved with the intention of manufacturing small devices and maintaining quality for the finished part.

Micromachining has become popular as a new technique that allows the manufacture of micro components. The term micromachining is related to the fabrication of geometries of less than 100 micrometers in any direction using any available method [2]. Micromachining demands new machine designs, including not only novel structural elements, but also new actuators, sensors and controls [3]. Designers of these new machines strive to reduce cost without sacrificing performance, that is, micromachines need to achieve precisions that are comparable or better than what is found in current CNC equipment.

In this work, techniques for the development of low cost, high precision microactuators are studied. In particular, the application of solenoids for the development of electromagnetic actuators is explored.

The scope of this study covers the development and testing of a micropositioner for one axis. The final goal of this work was to develop a positioning system for a µEDM machine. This article is organized as follows. First, a literature review section that covers micropositioning systems is presented. Then a short description of the individual elements of the analyzed actuator is presented with an overall description of how each part is interconnected. The micropositioning system is described in depth as a whole, and then the instrumentation system for data collection and control is described. Results are analyzed and discussed. Finally conclusions are presented.

Literature Review

Micropositioners are designed to obtain high precision positioning, in the range of micrometers, with high repeatability. The current trend is to achieve long displacement paths without sacrificing resolution.

The use of small synchronous linear motors has been documented [4,5] as an alternative for micropositioner construction. The need for special lithography equipment reduces the capability of construction of this type of motors. Other commercial alternative is the use of PZT actuators [6]. These types of actuators are capable of achieving positioning in the nanometer range. However PZT actuators require sophisticated power sources and, as a consequence, the cost of these control systems is high. PZT are suitable for small ranges of displacement, of just few micrometers. Cellular motors are capable of delivering elevated forces [7]. These motors are based on mechanical deformation of various large spherical elements (10 cm of diameter). The size and weight of cellular motors counteract the possibility of their application in small size machinery. Another alternative is the use of LVDT sensors as actuators, which increases accuracy and reduce complexity of the design [8]. However LVDT´s used as actuators have very limited force capability. The previous proposals require the use of special equipment for fabrication and expensive power sources and control systems.

Materials and Methods

A particular design of compliant mechanism (or flexure) was used in conjunction with a solenoid to produce a low cost actuator that achieves positioning within the order of micrometers. The actuator has the ability to achieve high precision positioning using a simple PWM technique. The technique is commonly used in open-loop control of solenoid valves, and consists of the application of a direct current signal with a variable duty cycle to the solenoid coil.

The cost of the complete system is maintained as low as possible using nonproprietary technology that does not rely on commercial precision positioning systems. For example micro positioning stages, based on high precision ball screws or piezoelectric actuators.

The target specifications of the micropositioner, consistent with this process, are listed on Table 1.

Parameter	Value
Control System	Open-loop
Repeatability	<1µm
Cost	Low
Total displacement length	30µm
Resolution	1µm

Table 1. Specifications of the micropositioner.

The system presented in this article uses a solenoid-flexure actuator as an innovative alternative for micropositioning. Solenoid actuator systems have the advantage of low cost, long cycle life and simple control systems. Figure 1 shows the solenoid-flexure configuration used in the system.

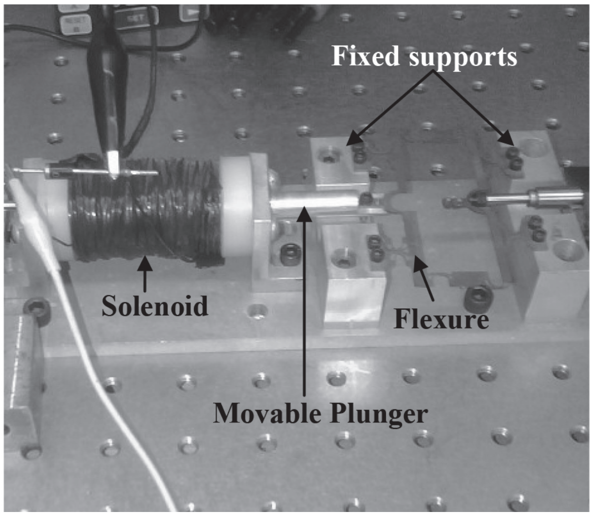

Figure 1. Solenoid-Flexure configuration.

Development and characterization of the solenoid

The proposed actuator's architecture is presented on Figure 2. The flexure acts as a reduction stage of the displacement produced by the solenoid to achieve position in the micrometer range. In use, the load (for example the dielectric tank for µEDM) is attached to the flexure.

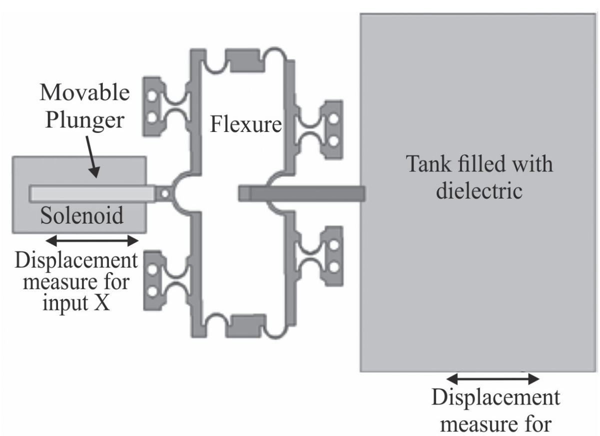

Figure 2. Micropositioner architecture.

A solenoid capable of generating the necessary force to drive the micropositioner was designed and constructed. Prior to assembly, the solenoid's capabilities were tested using the force sensor proposed by Flores et. al. [9]. The sensor is basically a load cell that is hooked to the plunger. A control current is passed through the solenoid, which causes the plunger to be displaced. The load sensor measures the force, which is recorded as a function of the current density. The force test setup of the solenoid is showed in Figure 3.

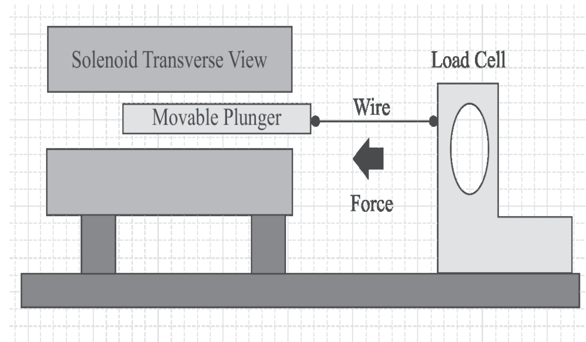

Figure 3. Solenoid force setup.

Actuator construction

The flexure is attached to the movable plunger. When the solenoid is energized the solenoid's magnetic field induces motion on the plunger. The force that the solenoid produces is proportional to the current that flows through the coil and the number of turns in it [10].

The flexure acts as a spring and opposes the motion of the movable plunger. The flexure transmits a multiple of the force that was produced by the solenoid to the tank, resulting in a controlled smooth motion. The tank uses pneumatic guides to reduce friction.

Using f*inite element analysis (*FEA) simulation, it was determined that a 2N force was necessary to obtain the desired displacement (30µm) at the output of the flexure. Figure 4 presents the FEA analysis of the flexure. The flexure geometrical characteristics are:

- Displacement reduction ratio 10:1
- Maximum output travel 30µm
- Dimensions 78.5mm X 59mm
- Thickness 1mm

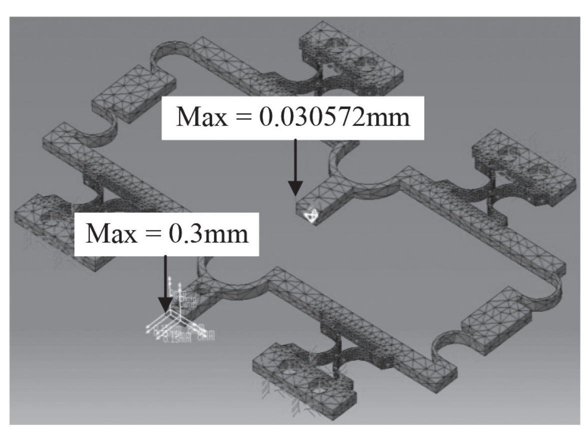

Figure 4. Flexure FEA analysis for displacements.

Actuator's complete assembly

Figure 5 shows a model of the micropositioner system and the load (tank). The flexure is the link element between the mass to be positioned and the actuator constituted by the solenoid-plunger. Although they are not shown in the figure, the tank was mounted on aerostatic guides to reduce friction.

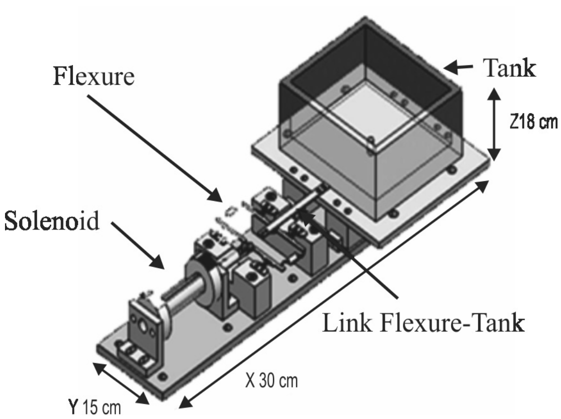

Figure 5. CAD model of the micropositioner assembly.

Data acquisition and control system

Figure 6 shows a diagram of different stages that constitute the open-loop position control system and the data tracking system for the micropositioner.

Both systems have an interface written in LabView and runs in the same PC, which controls the percentage of the solenoid force that is applied to the flexure changing the duty cycle of the PWM control signal. This method allows a gradual application of force to the solenoid [11].

The deformation of the flexure and the resulting displacement are controlled by the solenoid force. The data tracking program records position data from the micropositioner.

The data recorded consist of the values of position reported by the LVDT in contact with the tank, and the percentage of power supplied by the solenoid to the micropositioner in form of the width of the PWM signal.

The LabView program communicates with a microcontroller using a serial communication port. The microcontroller drives the current to the solenoid using a commutation electronics stage based on a bipolar junction transistor of NPN type.

The microcontroller was programmed in language C and receives instructions from the LabView program, which controls the power stage of the solenoid.

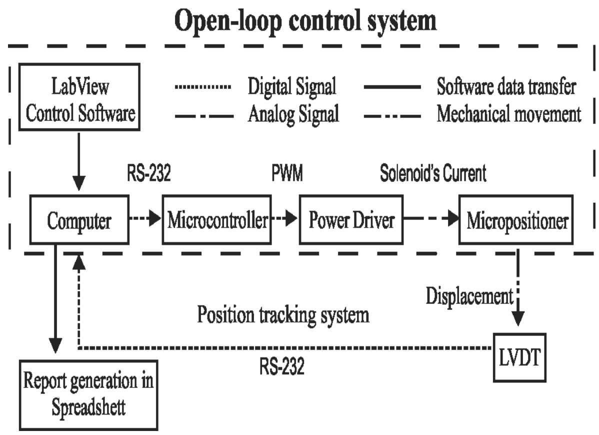

Figure 6. Block diagram of control and data acquisition systems.

Figure 7 shows the experimental setup that was used to test the micropositioner displacement. A Sony LT20 counter attached to a Sony DG810BL LVDT digital gauge was used to measure the displacement. The digital gauge factory specs report an accuracy of ±1 µm and a resolution of 0.5 µm with a measuring range of 10 mm. The gauge was attached to the movable plunger to measure the input displacement. Only one probe was available, and therefore it was also used to measure the output displacement of thank.

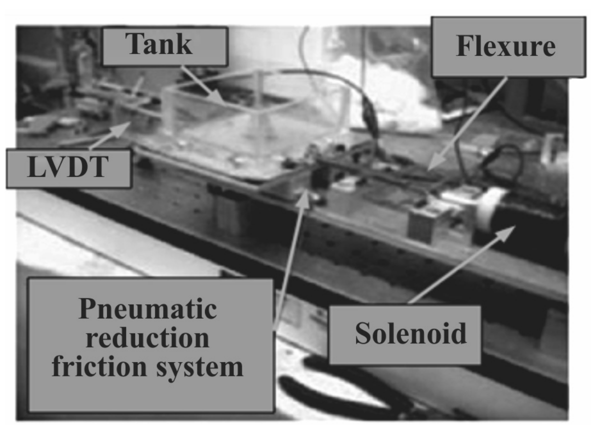

Figure 7. Experimental setup for micropositioner test.

Methodology for system analysis

In order to characterize the Micropositioning system with load (i.e., the tank filled with dielectric fluid suitable for µEDM), a series of tests were conducted in random order as suggested by a DoE develop for system analysis. Data was collected from each test for posterior analysis and discussion.

Hysteresis behavior

A series of 32 experiments, resulting from a DoE of the type 2^5 with replicates, were conducted to analyze the effect of different control parameters on the hysteresis. Five control parameters were selected to be modified in the experiments. The parameters that were modified and the levels for each one are shown in Table 2.

Parameter	Low level -1	High Level +1
Time interval (ms)	100	200
Carrier PWM (KHz)	1.22	5.04
Region	25.00%	45.00%
Solenoid Position	1	2
Voltage (V)	20	25

Table 2. Parameters and levels modified in hysteresis behavior test.

Ideally, the selected combination for operation of the micro actuator should present the lowest slope and a smallest hysteresis area. The final point achieved by the micropositioner in consecutive repetitions should be the same to allow for accurate positioning.

Results

Figure 8 shows the results of the application of a variable signal in the coil against the force measured by the load cell. The PWM percentage of the signal was increased from 0 to 35%, at which level it was maintained for a second, and then decreased back to 0%. As seen in the figure, at the beginning of the test the wire that connects the plunger with the load cell is loose. Consequently a displacement from the plunger is required to remove the slack. This is seen as a force equal to zero being reported from 0% to 20% of the PWM signal.

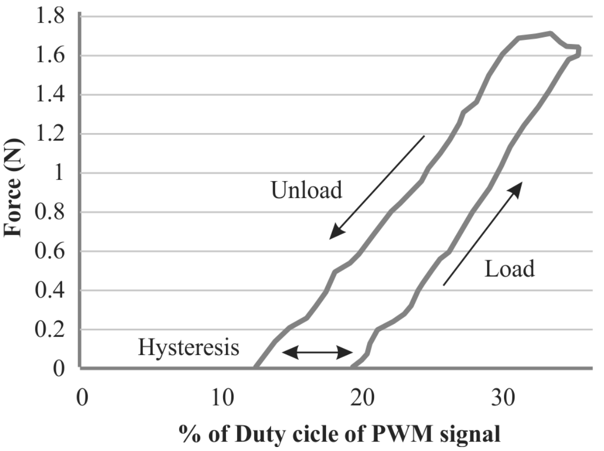

Figure 8. Force vs PWM test for the solenoid.

Results reveal that the relation between displacement and force is not linear. The solenoid presents hysteresis, an electromagnetic saturation point above which the solenoid is not capable of delivering more force to displace the movable plunger to deform the flexure. Once this point is reached, increasing the width of the PWM signal, increases power consumption, without increasing the available force. The saturation effect is shown in Figure 9.

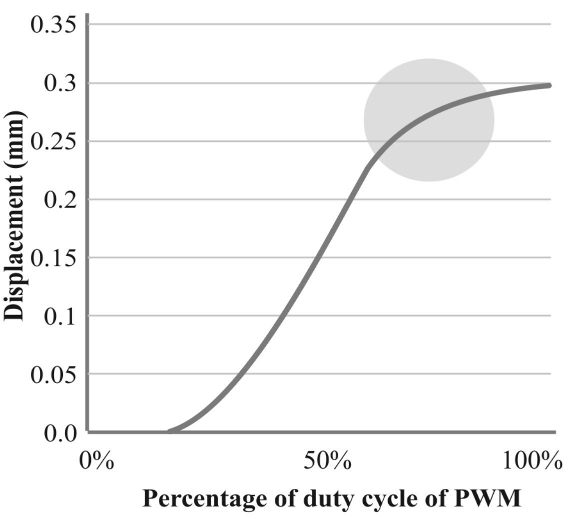

Figure 9. Saturation region of the solenoid.

The results also showed that the movable plunger was able to produce a displacement in the range of 300µm. This range is enough to generate the desired output after the movement reduction by the flexure. The micropositioner was analyzed on a semi-static regime to reduce the inertial force effects produced by the mass. This regime is consistent with the requirements of the EDM process.

After analysis of the resulting graphics for each test, the parameters shown in Table 3 were selected as the best for operation.

Parameter	Level
Time interval between consecutive position increments (ms)	200
PWM carrier frequency (KHz)	1.22
Operation region	Region 2 (45%)
Solenoid position	Position 2
Voltage applied to the solenoid (Volts)	20

Table 3. Best combination of parameters for micropositioner operation.

Figure 10 shows the resulting displacement pattern with the selected parameters. Hysteresis behavior was reduced and the maximum displacement achievable before saturation of the solenoid was reached.

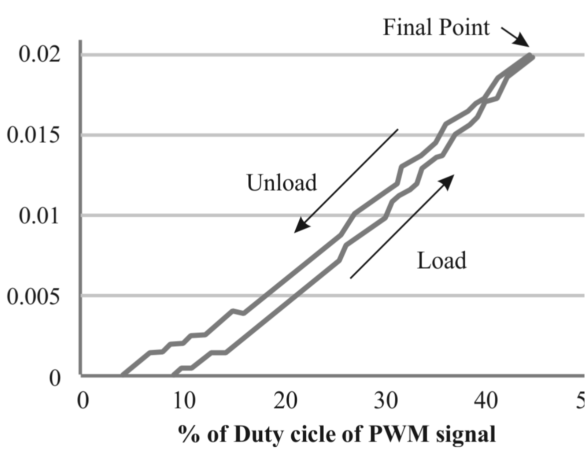

Figure 10. Best displacement achieved with selected parameters.

End point error test

The micropositioning system was tested over a range of control parameter combinations. Eight consecutive displacements of the micropositioner were measured.

The first maximum displacement achieved was defined as the desired target position. And consecutive measurements were made using this position point as reference for the seven remaining final positions differences. A statistical average of 0.429 µm was reported as error by these tests.

These tests showed that the error on final position of the systems was kept within target specifications. The resolution of the LVDT that was used for the data acquisition was a bottleneck for the analysis of capabilities of the system.

The estimated resolution of the system derived from the statistical analysis of error was under 0.5 µm, which is in the range of uncertainty of the LVDT employed.

Discussion of results

The hysteresis behavior of the micropositioner was affected by various parameters, including the friction of the system. Aerostatic guides were used to reduce the friction of the tank. Friction reduction leads to an increase of displacement range and reduction on the initial force needed to overcome static friction. The use of different friction reduction systems like lineal ball bushing bearings or magnetic sustentation could improve the positioned performance with and increment in cost.

The core of the solenoid was made with commercial low carbon steel, which is not ideal for electromagnetic applications because of the electromagnetic hysteresis behavior that produces heat at the core and reduce linearity of magnetization. The use of a core made in silicon steel could reduce hysteresis and improve linearity of the power application by the solenoid.

An important limitation inherent to compliant mechanisms is their response to dynamic loads. The flexure is not capable of transmitting great force to the tank because it deflects under the action of both the input force and the load at the output. Therefore, the microactuator was tested on quasistatic regime, similar to what is necessary for the µEDM process.

The positioning control system needs to account for hysteresis behavior if the micropositioner is intended for use in multi-axis interpolated operations. The use of a hysteresis model for prediction of behavior like the Preisach hysteresis model could be employed.

Conclusions

A micropositioner system based on a solenoid-flexure was proposed. The manufacturing and assembly of the system was based on low cost elements.

An open-loop control program for the micropositioner was developed. The data tracking system was capable of acquiring information for future analysis of micropositioner behavior using an LVDT as sensor. The behavior of the flexure was evaluated and a reduction in displacement of 10:1 was achieved.

The open-loop control program uses algorithms written in language C and LabView. The program runs over a microcontroller and is monitored and controlled by a PC running LabView using a serial low cost interface based on the protocol RS232.

The micropositioner displacement presents a non-linear behavior with a non constant slope and hysteresis. The system presents a delay in response because of the static friction presented at the solenoid. The positioning system proposed was able to achieve the target performance specifications.

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