A PMSM Driven Rotationally Oscillating Micro Drill

Handan Nak[1] and Ali Fuat Ergenç[1]

[1]Dept. of Control and Automation Engineering, Istanbul Technical University, Istanbul, Turkey
handan.nak@itu.edu.tr, ali.ergenc@itu.edu.tr

Abstract

In this paper, a novel control methodology for a micro injection mechanism with a permanent magnet synchronous motor (PMSM) is presented. The shaft of the motor is formed by micro pipette holder which houses the injection pipettes for piercing. The aim of the control system is to generate smooth oscillation at the tip of micro glass pipette with adjustable frequency and amplitude. These rotational oscillations facilitate the pipette to pierce the membrane of the cell with minimal biological damage and material consumption. Simulations are conducted to verify the performance of the proposed control methodology. Experiments demonstrate that with designed mechanical structure and control system tracking of rotational motion is achieved in accordance with total micro-drilling task.

1. Introduction

In recent years, advances in technology obtained a significant interest in medical areas. The mainstream of technology which is utilized in biomedical area is biomechatronics, which is the combination of electrical, computer and mechanical engineering. In micro scale, the most common application of biomechatronics is cellular micro manipulation. Micro manipulation is a combination of push, pull, orientation, deformation and injection of microscopic objects, such as cells, biomolecules, and viruses. Micro manipulation techniques are mainly used in reproductive biology, stem cell and transgenic animal research. The most common practiced processes are intracytoplasmic sperm injection (ICSI), pro-nuclei DNA injection, transgenic animal development, injection of mouse, zebrafish and other oocyte, gene therapy and viral studies [1].

Conventionally, micro manipulation process is performed manually, however since the past decade most of the manually handled instruments have been replaced by automatic electronic ones that are more fast, accurate, stable and reliable. Studying with sensitive micro materials such as cells, sperm, DNA needs special effort, training and performance. Most steps of a micro manipulation process require fine control of both position and force simultaneously, which is difficult for a human operator to accomplish consistently. Even for a well-trained operator, the success rate can still be low and economically not viable [2, 3]. Hence, there is a great demand for automated systems that can eliminate human involvement to the manipulation process.

As in macro world, micromanipulation systems consist of actuator, controller and sensor with software for sensor data processing, and manipulator planning and control. Manipulators are physical structures linked to the rest of the system such as micro gripper, micropipette, nano probes or specially designed micro objects. Automation requires real-time control of the position, orientation, and force applied by the manipulator to meet the system objectives by planning motions of manipulated object [2].

Significant research has been carried out for automatizing cell injection process. Sun et al. developed an autonomous 3-DOF micro robot system to accomplish a cell injection task on mouse embryo [4]. They used a holding micropipette for immobilizing a single mouse embryo, and a visually servoed micro robot for automated cell injection. Matsuoka et al. developed an automatic micro injector for mouse ES cells and rice protoplasts [5]. Wang et al. presented a vacuum-based embryo holding device in a fully automated microrobotic system for microinjection of zebrafish embryos [6]. Some researchers study on automatic batch micro manipulation [7-9]. There are lots of studies that focus on positioning and transferring of cells; visual servoing for orienting the polar bodies of mouse embryos in [10], a rotational positioning method based on the microscopic vision in [11], and an image-guided micro positioning system in [12].

Several groups have improved the conventional micro manipulation technology, a pulled sharp glass pipette to penetrate the cell membrane, contributing to the rupture of cell membrane. One of the most commonly used technology Piezo-drill©, which uses axial impact motion generated with piezo actuators [13]. This technology mandates to use a column of mercury near to the pipette tip to reduce the lateral motions and increase the effect of the axial motion. This technique is widely used despite the existence of the mercury. A novel piercing technology is proposed by Ergenc and Olgac called as Ros-Drill, a mercury free rotationally oscillating micro drill to overcome this issue[14, 15]. The technique uses a high speed rotation injector pipette to produce a rotational oscillation at the tip to drill the cell membrane. They utilize a brushed direct current (dc) motor for motion generation. The rotational oscillation amplitude of the device is limited to 0.1^{o} and the frequency to 100 Hz. A flexible coupling is placed in between the micro pipette holder and the dc motor. This coupling transmits angular motion from the motor to the micro pipette holder. Due to these construction constraints, during rotational oscillation of the micro pipette holder, pipette tip has some unwanted whirling and lateral motion [14].

In this paper, the authors aim to design and manufacture a rotationally oscillating micro drill that is easy to use, mercury free, and capable of adjusting the amplitude and frequency of the oscillations to use on mouse eggs and Caenorhabditis elegans in piercing experiments. In the design, the micro pipette holder form the shaft of the motor, thus the construction does not require any coupling and extra bearings that causes undesirable lateral motion and effects in micron order. This paper only focuses on obtaining oscillation motion with adjustable amplitude and frequency. It is preferred to use permanent magnet synchronous motor (PMSM) to achieve more sensitive and smooth oscillations. By using this design it is thought that cell and pipette damage and waste will be decreased and effectiveness of the system and cell viability will be increased.

This paper is organized as follows. The next section presents the mathematical model of PMSM. In Section III proposed oscillation topologies are presented, and some simulation studies are conducted. In Section V experimental studies are presented. Finally, in Section VI the study is reviewed and future work is discussed.

2. Mathematical Model of PMSM

A 2-pole permanent magnet synchronous motor (PMSM) is depicted in Fig. 1. It has 3-phase, wye connected stator windings and a permanent magnet rotor. The stator windings are identical windings displaced 120°, each with N_s equivalent turns and resistance R_s and sinusoidally distributed [16]. PMSM is commonly modelled and studied in *dq* reference frame to reduce the complexity of differential motor equations and to study more efficient and simple control strategies.

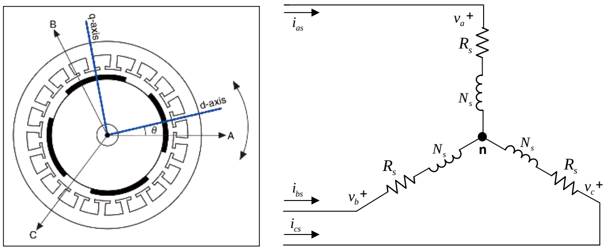


Fig. 1. Two-pole, 3-phase brushless dc motor.

The voltage and electromagnetic torque equations of PMSM in *dq* reference frame can be written as [15]

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega_r L_q \\ \omega_r L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \lambda_m \end{bmatrix} \tag{1}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_m i_q + \left(L_d - L_q\right) i_q i_d\right) \tag{2}$$

where v_d and v_q are *dq* axis components of stator voltages, i_d and i_q are *dq* axis components of stator currents, L_d and L_q are *dq* axis stator inductances, R_s is stator winding resistance, λ_m is permanent magnet flux linkage, ω_r electrical rotor speed, T_e is electromagnetic moment, P is number of poles and p is the derivative operator.

The dynamic mechanical equation of motor system with mechanical load is obtained as

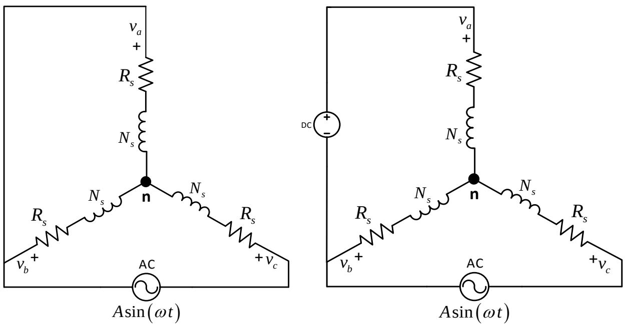
$$T_e - T_L = J\frac{d\omega}{dt} + B\omega \tag{3}$$

where T_L is load torque, ω is mechanical rotor speed, θ is mechanical rotor position, J is moment of inertia and B is viscous damping.

2. Proposed Oscillation Methods

The main difference between piezo drill and rotationally oscillating drill is motion type. While pizeo drill has axial impact type action, rotationally oscillating drill rotationally oscillates the micropipette holder at selected frequency and amplitude. It is important to be able to adjust frequency and amplitude separately in a wide range for different micro manipulation tasks such as sperm head seperation, membrane piercing and oolemma penetration.

In micro manipulation process, since the motor only oscillate at small amplitudes and never need to take a full turn, there is no need for a three phase inverter. A sinusoidal voltage that applied between two motor terminals is sufficient. However, one problem with this sense is that motor shifts at the same time as it oscillates. To overcome this problem and immobilize the motor, a dc voltage is utilized. When dc voltage is applied between two phases of the motor, a dc magnetic field occurs in the air gap, and rotor is aligned. If an ac signal is applied to motor terminals after rotor is aligned, motor begins to oscillate at the frequency of source signal. Another method is connecting two phase of the motor to align rotor but this method could not meet the request for relatively high sinusoidal amplitudes adequately. In this manner, these two different topologies that can be used to oscillate the motor are given in Fig. 2.



(a) (b)

Fig. 2. Different topologies for oscillating the motor.

To investigate the performance of proposed oscillation topology for PMSM, the simulation diagram in Fig. 3 is constructed in Matlab/Simulink.

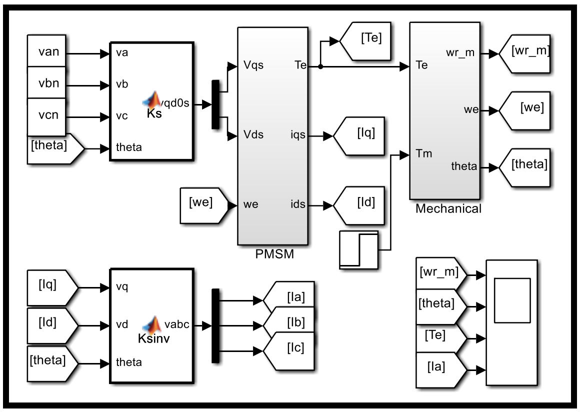


Fig. 3. Block diagram of PMSM.

Note that, in the simulation diagram v_{an} , v_{bn} and v_{cn} are phase to neutral voltages. Therefore, one has to calculate these voltages for the topologies in Fig. 2. For example, the phase-to-neutral voltages for topology in Fig. 2 (b) can be written as

$$\begin{aligned} v_{an} &= v_a - v_n = \frac{V_{dc}}{2} - \frac{V_{ac}}{2} \\ v_{bn} &= v_b - v_n = -\frac{V_{dc}}{2} - \frac{V_{ac}}{2} \\ v_{cn} &= v_c - v_n = -\frac{V_{dc}}{2} + \frac{V_{ac}}{2} \end{aligned} \tag{4}$$

where V_{dc} is the dc voltage and V_{ac} is the ac voltage.

In the experimental studies Maxon EC-powermax 305014 is used, and simulations are run with this motor specifications that is given in Table 1.

Table 1. Motor specifications.

Values at nominal voltage		
Nominal voltage	V	36
No load speed	rpm	16700
No load current	mA	485
Nominal speed	rpm	16200
Nominal torque (Max. cont. torq.)	nNm	94.2
Nominal current (Max. cont. cur.)	A	5.03
Stall torque	nNm	3510
Stall current	A	171
Max. efficiency	%	89.9
Characterictics		
Thermal resistance phase to phase	Ω	0.21
Thermal inductance phase to phase	mH	0.0368
Torque constant	mNm/A	20.5
Speed constant	rpm/V	466
Speed/torque gradient	rpm/mNm	4.78
Mechanical time constant	ms	1.67
Rotor inertia	gcm^2	33.3
Other Specifications		
Number of pole pairs		2
Number of phases		3

In the first simulation, the motor is supplied by only a dc voltage source. Positive terminal of the source is connected to phase *b*, negative terminal is connected to *a* and *c* phases. The amplitude of voltage is 0.2 V, and initial rotor position is π/4. As expected, after the rotor is once aligned with phase *b* no motion is observed.

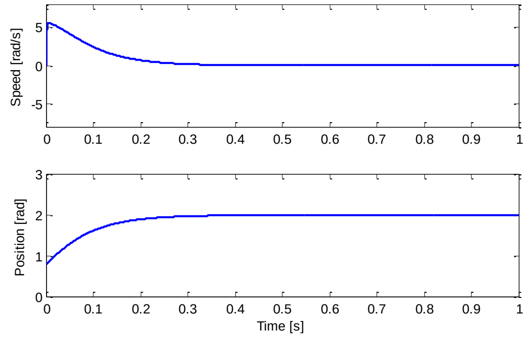


Fig. 4. Simulation results for only a dc supply.

In the second simulation, only a sinusoidal signal source with frequency of 50 Hz and amplitude of 1.5 V is connected between two terminals of the motor. The results are given in Fig. 5. As seen, the motor oscillates at the source frequency, however the oscillations are not stable and the motor is shifting.

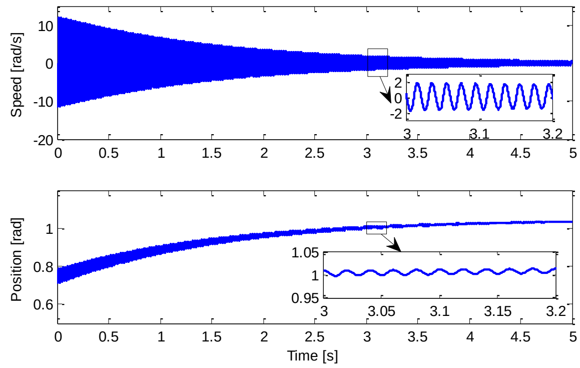


Fig. 5. Simulation results for only an ac supply.

In the last simulation, the topology in Fig. 3 (b) is used. The amplitude of dc voltage source is again 0.2 V and the initial rotor position is π/4. For ac voltage a sinusoidal signal with frequency of 50 Hz and amplitude of 1.5 V is used. The results are given in Fig. 6. As seen from the figure, stable oscillations are obtained as desired.

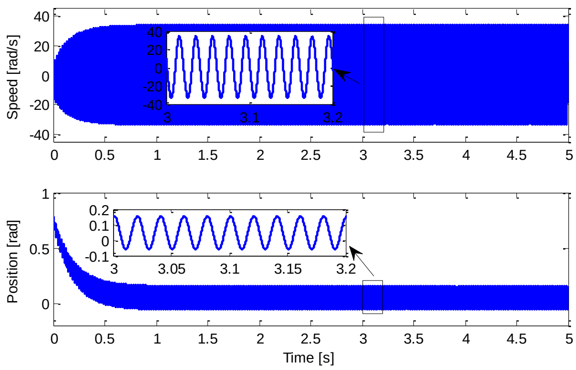


Fig. 6. Simulation results for the topology in Fig. 3 (b).

4. Experimental Studies

In the experiment set-up two linear amplifiers, for dc and ac signals individually, are used as the motor driver. For reference signal a pure sinusoidal reference trajectory is purposely selected to avoid unnecessary excitation of the natural vibration modes of micro pipette holder. To generate the sinusoidal signal with desired frequency and amplitude a voltage controlled oscillator (VCO) structure is used. For this purpose, a monolithic function generator integrated circuit, XR-2206 which is capable of producing high quality sine waveforms of high-stability and accuracy is utilized. The output waveform can be both amplitude and frequency modulated by external voltages independently. In the circuit design, the components of VCO structure are chosen to be able to change the frequency of the signal at 0-1500 Hz and the amplitude at 0-5.4 Vpp. The position feedback is provided by an incremental encoder, which is attached to the shaft of the motor. The encoder generates 5000 pulses/rev. when used in quadrature mode; it determines the sensitivity of position feedback with 0.018° increments.

For control of the whole system (to control the amplitude and frequency of the reference sinusoidal signal, amplitude of dc signal), Beckhoff CX2030-0111 industrial computer is utilized with the following I/O modules: A 4-channel -10 .. + 10V analog output unit, a 4-channel 0..10V analog input unit, an 8-channel digital input/output and an incremental encoder module. Two 24V-10A power supplies were used for dual supply of linear operational amplifiers and VCO module. The block diagram of the system and the entire set-up are shown in Fig. 7 and 8 respectively. As seen from figures, the pipette holder is formed the shaft of the motor and no additional bearings are needed.

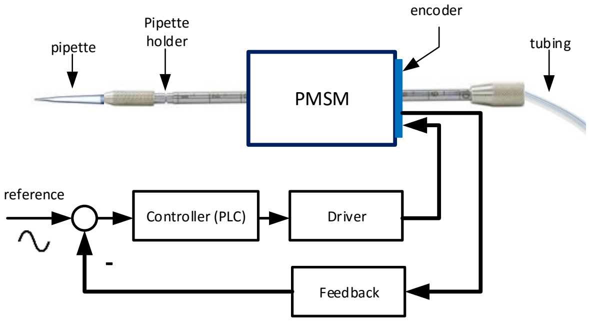


Fig. 7. Micro manipulation system block diagram.

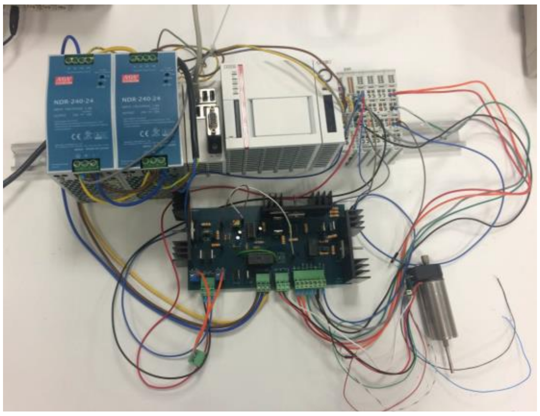


Fig. 8. Micro manipulation system set-up.

Programming of Beckhoff industrial computer is done using TwinCat software. In order to generate the desired ac and dc voltage, operate the operational amplifiers as required the necessary software is builded with TwinCat, and a control screen is prepared as shown in Fig. 9 to monitor and control the entire process.

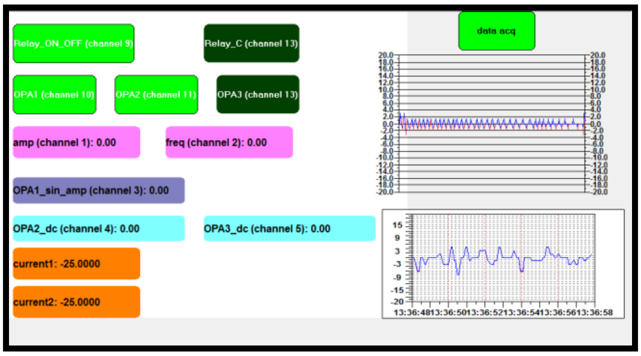


Fig. 9. Automation system main screen.

The results of the some of the experiments with the topology in Fig. 2 (b) are given in Figs. 10-12. In all three cases the amplitude of voltage source is 1.5 V and the amplitude of dc voltage source is 0.2 V. The frequency of sinusoidal voltage is 50, 100 and 250 Hz respectively.

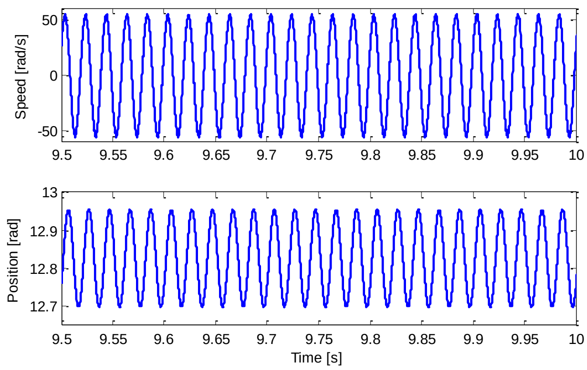


Fig. 10. The experimental results for the topology in Fig. 2 (b) for frequency of 50 Hz.

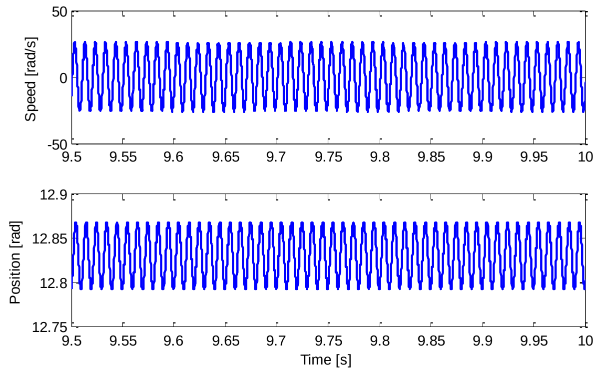


Fig. 11. The experimental results for the topology in Fig. 2 (b) for frequency of 100 Hz.

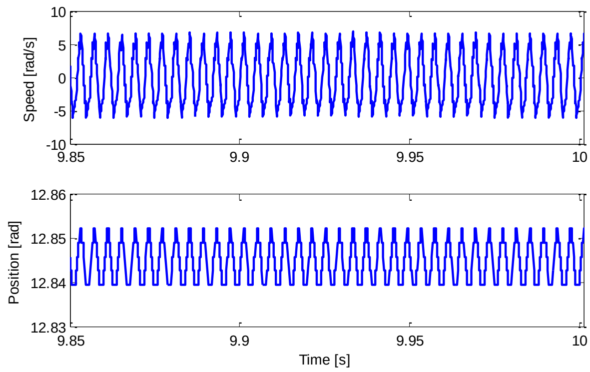


Fig. 12. The experimental results for the topology in Fig. 2 (b) for frequency of 250 Hz.

As seen from figures, the motor oscillates at the source frequency. When frequency is increased, the amplitude of position change decreases as expected. This means that when studying at high frequencies, supply voltage should be increased by control algorithm to satisfy the desired oscillation.

6. Conclusions

In this paper a novel technology is reported for motion generation of micro drilling process by utilizing a PMSM. The focus of this paper and most critical part of the whole project is design a system that targets PMSM to oscillate with desired frequency and amplitude, and control the entire system. Both simulations and experimental studies exhibits that the goal has been reached. Furthermore, in this design, micro pipette holder is used as motor shaft, so the size of the device is reduced, the coupling is not used and no additional bearing is needed. It is aimed to use this device especially in veterinary science, embryonic biology, medicine and biotechnology research areas.

As future work, the developed device may be used with sperm preparation (separation of the tail head), zona piercing and membrane piercing for sperm injection into mouse oocytes and some C. elegans studies such as generation of transgenic animals and RNA interference.

7. Acknowledgment

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7. References

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