Sensorless position control of voice-coil motors for needle-free jet injection

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Abstract—This paper demonstrates a simple method for sensorless position estimation and control of a linear voice-coil actuator. Such actuators are currently used in needle-free jet injector prototypes. The sensorless method makes use of the position dependent impedance of the voice-coil at high frequencies to produce an estimate of coil position. This is achieved through the addition of a high frequency signal to the motor’s driving signal.

The position and frequency dependence of the voice-coil impedance is presented. Also the ability of this sensorless position estimation method to control position to a square set point is demonstrated using PID control. A jet injection is performed in order to observe the ability of this position sensing method to track position in such a high speed application.

I. INTRODUCTION

Needle-free jet injection is a transdermal drug delivery technique that uses a thin, high-speed jet of fluid to penetrate the skin and deliver the fluid drug. Jet injection has been under investigation since the 1860s, and has seen use in applications ranging from mass immunization programs to insulin delivery [1]. Typically, liquid jet injection involves forcing the fluid drug through an orifice 50 µm to 360 µm in diameter at pressures up to 35 MPa, creating a jet travelling at a speed in excess of 100 m/s capable of piercing the skin.

Needle-free delivery provides several advantages over conventional needle-based delivery. These include improved speed, no risk of needle-stick injury, and, in some cases, enhanced drug efficacy [1]. Low acceptance of liquid jet injection has generally been attributed to variable reactions at the injection site. Much of this variability is thought to be caused by the lack of control over the jet speed and injection depth [2]. More recently developed injector designs, using controlled actuators such as voice coils (Fig. 1) or piezoelectric devices, provide a greater ability to control these parameters when compared to conventional spring or compressed air based injectors [3].

One drawback inherent in the use of controllable actuators is the need for a sensor to provide coil position information for feedback control. The sensor increases the cost and complexity of the jet injector, and sensor failure can result in potentially dangerous injection errors. This can be avoided by using self-sensing actuators, [4], [5] where position is determined via a property of the actuator itself that varies as it moves. In this paper, we investigate the use of self-sensing in a voice coil for jet injection, using the variation of the motor’s high-frequency impedance with position as the sensing parameter.

II. BACKGROUND

Sensorless position measurement in electric motors has been most thoroughly explored in the context of multi-phase linear and rotary motors [6], where relative position information is required for brushless operation. Here, the most common technique relies on measurement of the back-emf generated by the motion of the motor, which is only available when the motor is moving and cannot be used to measure absolute position. Use of an observer informed by both the motor voltage and the motor currents can yield improved results, especially at low speed, but still cannot provide absolute position. Inductance-based methods can
determine absolute position, but require inefficient motor drive parameters and rely on very high-speed analog measurements.

There have been considerably fewer reports of sensorless position estimation in single-phase voice coil actuators. Observers have been used to estimate position from back-emf and coil current [4, 7, 8] but these are not suitable for absolute positioning due to integration drift. Inductance measurements have been used to determine absolute position in voice coils [9], although only in the absence of motion.

The frequency-dependent variation of voice coil impedance and its variation with position have been extensively discussed in the context of loudspeaker design, where they introduce distortions in sound reproduction [10], [11]. The precise nature of the position dependence of the frequency response depends strongly on the motor construction, and includes effects from inductance variation, hysteresis loss in iron components, and eddy current losses in conductive components within the coil. As the impedance can be accurately measured at a single frequency well above those associated with jet injection, we chose to investigate it as a tool for absolute position estimation.

III. METHODS

A. Experimental Apparatus

Impedance characterization and closed-loop control were performed on a modified version of the voice-coil actuator used in previous needle-free jet injector prototypes [3]. It has a stroke length of 30 mm, DC resistance of 6.0 Ω and force constant of 6.5 N/A. A LabVIEW cRIO 9004 real time controller was used with NI 9223 and NI 9263 modules for analog signal input and output, respectively. The coil voltage and current were measured to 16-bit resolution at a rate of 1 MHz. A linear power amplifier (Apex Microtechnology PA75) was used in a trans-impedance configuration to amplify the input voltage signal and set the current sent to the voice-coil.

Jet injection tests were done using a voice-coil of identical construction, but with a DC resistance of 9.6 Ω and a force constant of 9.0 N/A. The actuator was driven by two power amplifiers (AE Techron 7224) configured in series. LabVIEW 2011 FPGA and LabVIEW Real-Time software were used for the signal processing and control logic for both experiments.

B. Control Architecture

Fig. 2. Block diagram of the sensorless closed loop control process. The lower limb represents the signal processing involved in producing a position estimate from the sensorless method.

Fig. 3. The frequency response magnitude (top) and phase (bottom) of the voice-coil actuator, are shown at 0 mm, 15 mm and 30 mm stroke position.
involves both the addition of the high frequency position measurement signal and the signal processing shown in the lower limb of the block diagram. The measured voltage across the voice-coil is filtered through a 2nd order high pass Butterworth filter to isolate the measured voltage components at the frequency of the position measurement signal. The rms filtered voltage is calculated over 1000 samples (1 ms) and a 3rd order polynomial model is used to translate the result into a position estimate (model labelled as LUT in Fig. 2 for simplicity).

C. Experimental Procedure

Testing to measure the frequency response was conducted using a white noise input while the voice-coil was held in a fixed, known position.

Calibration of the sensorless position estimate required the measurement of the rms filtered voltage while position was independently measured. A potentiometer (ALPS RDC10) was mounted onto the voice-coil for this purpose. The coil was then manually moved through its stroke as these two parameters were simultaneously measured.

Control testing was performed using a 0.5 Hz square wave set point with an amplitude of 3 mm. This was conducted with the voice-coil unloaded.

A final test was performed to investigate whether the sensorless position estimation method could maintain accuracy during the rapid voltage and current swings required during a jet injection. This experiment involved rapidly increasing the motor voltage by 250 V in less than 10 ms. A high power voltage amplifier was used and the current was measured using the amplifiers internal sensor. Position was measured by a potentiometer simultaneously with the sensorless method.

IV. Results

A. Motor Impedance

The position and frequency dependence of the voice-coil impedance is shown in Fig. 3. The position measurement signal frequency is required to exhibit a sufficiently large change in impedance with position such that meaningful position estimates can be made. This suggests that the higher frequencies in Fig. 3 are more desirable. However an increase in the noise present in the impedance magnitude was observed with increasing frequency. 20 kHz was initially selected as the injection frequency as it appeared high enough to achieve useful position sensitivity, however this was increased to 30 kHz for the jet injection testing.

B. Position Estimation

The relationship between the rms voltage from the sensorless position estimation algorithm and the measured stroke position is shown in Fig. 4 for a moving coil. A 3rd order polynomial is fitted to these data to form the model for the translation of rms voltage into a position estimate. The standard deviation of the noise present in the position varies between 12 – 23 µm in a position equivalent sense over a 1 kHz bandwidth. Fig. 4 shows some hysteresis at extended stroke positions.

D. Control

A PID control scheme was implemented to control motor position, and tuned to be critically damped. Fig. 5A shows the controlled response to a square wave set point. The tuned control involved only PI control with proportional gain (Kc)
of 0.223 and integral time ($T_i$) of 0.1 minutes. The position can be seen to rise and settle to the set point within 100 ms.

D. Jet Injection

The position of the motor as measured by both the sensorless method and potentiometer during a jet injection of 190 µL is shown in Fig. 5B. The position estimation process is effective even for high-speed motion during the injection. The sensorless estimation deviates when the applied current changes, however, with peaks seen as the driving voltage rises and when it ceases. Noise at a frequency of 100 Hz (twice power-line frequency) can be seen in the sensorless estimation of position during the steady state portions of this result. This noise is particularly evident at the end of the stroke where the impedance to high frequency is greatest and is thought to be derived from the amplifier used for this testing.

V. Discussion

The sensorless position measurement method presented has demonstrated the ability to successfully control position in a critically damped manner (Fig. 5A). The response time during the step was limited by the maximum control voltage output. As this limit is reached during the step, the response time of the controller is increased.

The improved resolution of the data (and associated position estimate) measured with a trans-impedance amplifier is due to the limited representation of the measurements made available by the analog input module used. The rms voltage varies over a range of 4 V with the change in impedance over the stroke whereas current varies less than 10 mA. Consequently, the dynamic range when measuring the voltage is much greater than when measuring current.

Deviations observed during the jet injection test (Fig. 5B) at the points of changing input voltage are thought to be due to the sudden addition of high frequency (>25 kHz) components into the voice-coil voltage. This was supported by basic modelling of a blocked voice coil, which predicted the inability of the current filtering to fully remove these components of the driving signal. It was for this reason that the added high frequency signal was increased to 30 kHz for the jet injection testing. The magnitude of the peaks seen in Fig. 5B were noticeably reduced but not eliminated by this increase.

Currently, a Butterworth high pass filter isolates the position measurement signal from the driving signal. Despite the simplicity of this method it led to the success evident at low speed (Fig. 5A). In order to achieve the same success in high speed applications, the filtering process must be improved to more effectively separate the position measurement signal from the driving signal. An increase in the frequency of the added position measurement signal serves as an obvious first step in attempt in this separation. Given the successful control shown at lower speeds it is hoped that such improvement to the filtering process will deliver precise position measurements and lead to sensorless control of jet injection and other high speed applications.

VI. Future Work

Development of the process by which the position measurement signal is isolated from the driving signal will be important. As discussed above, this will involve improvement to the filtering used and investigation of the best frequency for the position measurement signal.

It will also be of interest to investigate the ability of this sensorless position measurement method when applied to voice-coils of varying design and geometry. This will provide insight into how widely applicable this method could be.

References