Adjustment of Needle-free Jet Injector Control to Account for Viscous Loss

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ABSTRACT SUMMARY

A needle-free jet injector (NFJI) that is actuated by a Lorentz-force actuator can deliver a jet of liquid drug through the skin in a controlled manner. This approach allows the delivery of a precise volume of drug to a predetermined depth within the subcutaneous and intramuscular layers of the skin. Voltage pulse tests using the NFJI have allowed us to determine the degree to which drug viscosity affects the speed of jet emission. A 3-D polynomial fit to the results enables the use of a single pulse test to estimate the viscosity of any fluid within the ampoule in less than a second. This estimate is then used to inform a feed-forward model that ensures that the fluid reaches the correct jet speed for penetration during subsequent injections.

INTRODUCTION

A needle-free jet injector (NFJI) is a device in which an actuated piston pressurizes a liquid drug contained within an ampoule. Our device uses a controllable Lorentz-force actuator to provide the force required for needle-free jet injection. A small orifice at the end of the ampoule allows the fluid to exit as a jet at speeds up to 200 m·s⁻¹ [1]. The fluid jet is able to penetrate into the subcutaneous and intramuscular layers of porcine skin [2].

The orifice of the NFJI is a cause of energy loss due to viscous dissipation in the fluid as it emerges from the ampoule [3]. As viscosity increases, the pressure loss between the piston tip and the exit of the orifice increases non-linearly. Accordingly, the NFJI requires more force in order to reach injection speed with fluids of higher viscosity.

The NFJI system relies upon an empirical model of the voltage:speed relationship in order to accurately attain the jet speeds required for a successful injection [2]. The purpose of this work is to expand this model to encompass fluids of viscosity higher than that of water.

EXPERIMENTAL METHODS

Pure water and diluted glycerol solutions were used to investigate the effect of viscosity upon the jet speed attained for a given voltage input. Glycerol solutions were created at concentrations of 30 %, 60 %, 75 % and 85 %, which, along with water, encompassed a viscosity range from 0.001 Pa·s to 0.1 Pa·s. The viscosity of each solution was determined using a rheometer (TA Instruments ARES-G2).

A series of “pulse test” experiments (Figure 1) was conducted on each of the five solutions, in which a voltage pulse energized the actuator to eject fluid from the ampoule. Voltages ranged between 50 V and 200 V. The period of each pulse was 20 ms; this period was sufficient to allow a jet to form and to reach a steady state speed (period between the dotted black lines in Figure 1). Actuator position was recorded by a displacement sensor.

During the steady-state period of a pulse test (15 ms – 19 ms) the actuator and the attached piston reached a constant speed which was found from the slope of a line fit to the blue trace in Figure 1. The jet speed was estimated by multiplying the actuator speed by the ratio of the area of the piston to the area of orifice. The jet speed reflects in part the degree to which pressure has been lost due to viscous friction in the orifice, assuming that the sliding friction of the piston remains constant between injections. The results of the pulse response experiments were fit using linear least squares (MATLAB polyfit, John D’Errico, 2012) to a ten-parameter polynomial forming a 3-D surface, thereby describing the dependence of jet speed on the applied voltage and fluid viscosity. The same fitting process was utilized to form another polynomial relating the viscosity to the applied voltage and the jet speed. A single voltage pulse experiment could then be used to estimate the viscosity of any unknown Newtonian fluid, and to select the appropriate model to use in the NFJI controller.

The estimation method was tested by subjecting five samples of solution with blindly-selected viscosity to a test of 160 V for 20 ms. The resulting jet speed was used to estimate the viscosity of each of the solutions and compared to estimates independently measured using a rheometer.

Figure 1 - Results of pulse test with applied voltage (red - left axis) and actuator position (blue - right axis). The dotted black lines outline where velocity was measured.
Each viscosity estimate was useful in informing a feed-forward model of the injector. The estimated viscosity value could be input as a parameter into the polynomial and the result evaluated. The equation formed was a 3rd order polynomial that predicts the required applied voltage to achieve a certain jet speed at the estimated viscosity during an injection.

Four tests were conducted whereby the feed-forward model set the voltage of the pulse based upon the desired jet velocity and the estimated viscosity of one of the unknown fluids. The resultant velocity estimate was extracted from the last millisecond of the pulse test and plotted against desired velocity.

RESULTS AND DISCUSSION
The fit to the results of the pulse experiments is shown in the contour plot of Figure 2. The plot shows a clear increase in the voltage required to achieve any given jet speed as viscosity increases. The polynomial was fit to the results of a total of 67 experiments; the RMS error of the fit was 3.844 m·s⁻¹. Relative to the range of jet speed, this fit can be considered sufficiently valid for prediction.

The results of the viscosity measurements using the NFJI (Figure 3) indicate that the test can be relied upon to estimate the viscosity with a mean error of 15%. The viscosity estimate for the 0.0209 Pa·s fluid was used to form a 3rd order polynomial as indicated in Figure 2. The results of using the feed-forward model to choose the applied voltage required to achieve a jet velocity (Figure 4) show that the derived polynomial can assist in achieving a desired jet speed with a mean error of 10.9%.

CONCLUSION
A series of pulse tests has evaluated the degree to which viscosity affects the jet that emits from a Lorentz-force motor-based NFJI. The results of these tests allow for a short 20 ms pulse test to estimate viscosity within 15% of its value. The viscosity estimate can be used to inform a feed-forward model for injection of the tested fluid at a desired velocity. Any remaining discrepancy between the desired injection speed and actual injection speed is compensated for in our system using feedback control (results not shown).

REFERENCES

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