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VIRTUAL LASH ADJUSTER FOR AN ELECTROMECHANICAL VALVE ACTUATOR THROUGH ITERATIVE LEARNING CONTROL

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ABSTRACT

The reduction of impacts which occur in electromechanical valve actuators due to the presence of valve lash have been largely neglected in the literature. Instead, the majority of work in this area has focused on impacts occurring elsewhere. As such, a controller is presented here to account for the impacts which occur during the release phase of the valve opening due to the presence of valve lash. A combination of feed forward and iterative learning control are used to achieve trajectory tracking during the release bounding the impact velocity by 0.4 m/s.

1 Introduction

Innovative technologies are required to further reduce automotive pollution and fuel consumption. One such technology is the electromechanical valve actuator (EVA). Valve timing in most automotive engines is fixed with respect to the piston position by a mechanical linkage called a camshaft. While reliable and effective, this constrains the optimization of the engine performance. The electromechanical valve actuator permits variable valve timing for greater flexibility by employing electromagnets to actuate the valves. Research has shown that variable valve timing can potentially reduce automotive emissions by 12% to 15% [1], improve fuel economy by 18% to 23% [2], and increase engine torque by 20% [3].

A typical electromechanical valve actuator is shown in Fig. 1. The valve motion is governed through the forcing of the armature by the opposing sets of electromagnets and springs. A typical operation begins with the armature held against either the upper or lower magnetic coil. This creates an imbalance between the opposing springs which will drive the armature across the gap when the current in the releasing coil is sufficiently reduced. As the armature nears the opposite side it is caught by and held against the remaining electromagnetic coil to complete the transition. Once again an imbalance is created in the opposing springs which is used to reverse the process. The spring forces are balanced when the armature is equidistant from each magnetic coil.

The inherent drawback of the electromechanical valve actuator is that it suffers from large impacts at several different locations due to the motion of the armature and valve. These impacts are excessively loud and may lead to actuator failure. Of particular interest to this paper are the impacts which occur between the armature and valve stem during the release of the armature.

As in conventional cam driven systems, the valves are not physically connected to the armature to allow for thermal expansion during operation. This ensures that the valve will always close against the valve seat. The gap between the armature and valve stem is denoted as the valve lash and can range between 0.1 mm to 0.5 mm depending on the thermal expansion of the valve. In a conventional cam driven systems a physical device, referred to as a lash adjuster, is used to account for the valve lash and avoid large impacts between the valve and the cam. Rather than redesign the actuator to include a similar device, which would increase packaging size and cost, the existing hardware can be utilized to achieve the desired performance

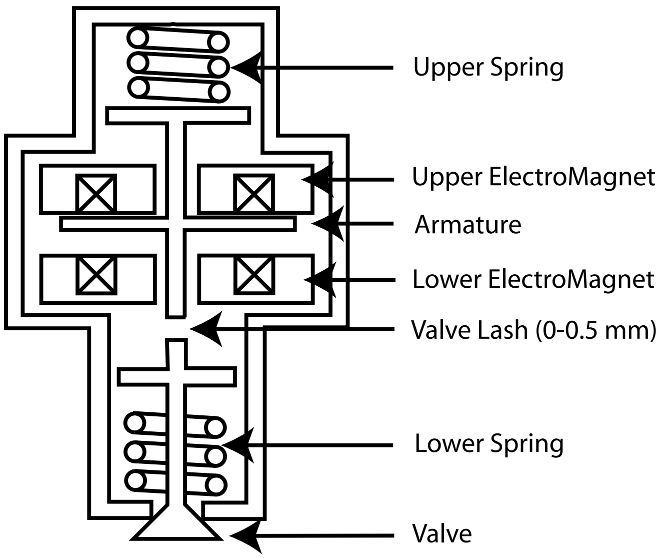

Figure 1. Electromechanical valve actuator.

through intelligent control of the command voltage to the electromechanical valve actuator.

Almost without exception the effects of valve lash are completely ignored in the literature. In most instances [4–8] the research is concerned with impacts which occur between the valve and valve seat and between the armature and magnets. However, at maximum valve lash the impact velocity is quite significant and can be as large as 2 m/s.

Impacts which occur due to the valve lash during a valve closing event are considered in [9,10]. Excitation of the resonate frequency corresponding to impacts between the armature and valve stem is avoided by a notch filter. In a valve closing procedure the armature and valve are initially in contact and therefore move as a single mass during the majority of the executed motion. It is only at the end of the travel when the valve is fully closed that the two separate. After separation the armature has less than 0.5 mm of travel remaining. Conversely, during a valve opening procedure the armature and valve are not initially in contact. Improper release of the armature can result in repeated impacts between it and the valve throughout the travel. These impacts are referred to as "chatter" between the armature and valve stem.

Release of the armature in the absence of valve lash is considered in [8]. The short delay between valve events at high engine speeds necessitates the quick release of the armature. The authors of [8] propose a technique which minimizes the release time and loss of potential energy. This solution is no longer ideal when valve lash is present and can result in impact velocities of up to 2 m/s.

The goal of this paper is to develop a controller capable of limiting these impacts below 0.4 m/s, referred to as soft release, without significantly increasing the transition time. As long as the initial impact between the armature and valve stem is kept below 0.4 m/s the resulting chatter is minimal. Feed forward control based on the theoretically required voltage necessary to coast the armature through the valve lash at 0.4 m/s is used to accomplish the soft release. Due to modeling uncertainty the theoretically required voltage cannot achieve the desired performance alone. Therefore it is augmented with an iterative learning controller to improve the performance from one valve event to the next.

2 Modeling the EVA's Release Dynamics

Using the model developed in [8] and defining the states of interest and the system input as;

z the distance between the armature and upper magnetic coil [m]
v the armature velocity [m/s]
i the current in the upper magnetic coil [A]
V_r the voltage applied to the upper magnetic coil [V]

the EVA's releasing dynamics are described by

$$\frac{dz}{dt} = v \tag{1}$$

$$\frac{dv}{dt} = \frac{1}{m}\left(-F_{mag}(i,z) + k_s(l-z) + k_{pre} - bv\right) \tag{2}$$

$$\frac{di}{dt} = \frac{V_r - ri + \chi_1(i,z)\,v}{\chi_2(i,z)}. \tag{3}$$

where m is the mass of the armature in kg, F_{mag} is the magnetic force generated by the upper magnetic coil in N, l is half the total armature travel in m, k_s is the spring constant of the upper spring in N/m, k_{pre} is the preload of the upper spring in N, b is the damping coefficient in kg/s, V_r is the applied voltage in V, r is the resistance of both the wiring and magnetic coil in Ω, $\chi_1 v$ is the back-EMF generated by the armature motion in V, and χ_2 is the inductance of the magnetic coil in H. The armature position and applied voltage are restricted to the sets $z \in [0, 2l]$ and $V_r \in [-180, 180]$ respectively due to the physical constraints of the magnets and actuator saturation.

The functions F_{mag}, χ_1, and χ_2 are given by

$$\chi_1(i,z) = \frac{2k_a i}{(k_b+z)^2} \tag{4}$$

$$\chi_2(z) = \frac{2k_a}{(k_b+z)} \tag{5}$$

$$F_{mag}(i,z) = \frac{k_a i^2}{(k_b+z)^2} \tag{6}$$

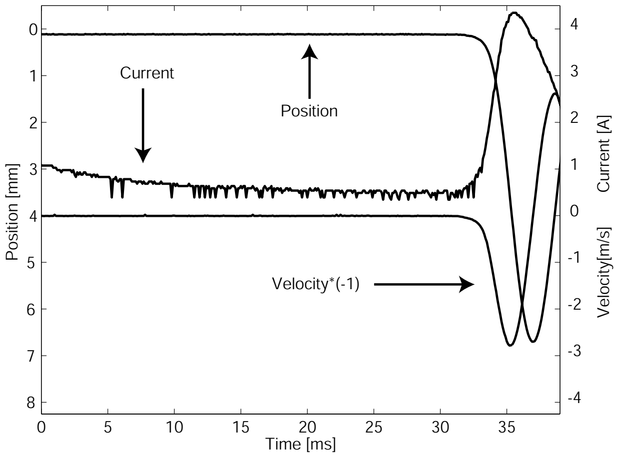

Figure 2. Free release of the armature.

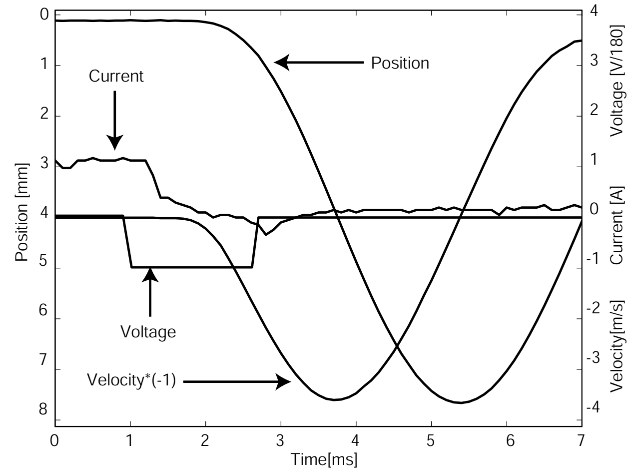

Figure 3. Release of the armature without valve lash present.

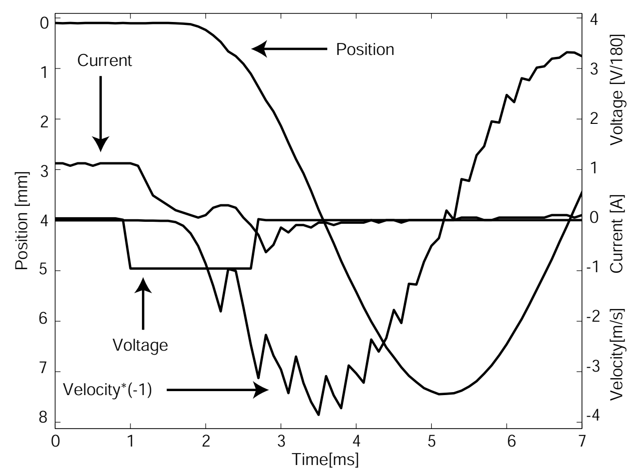

Figure 4. Release of the armature with valve lash present.

where k_a and k_b are constants. Eqns. (4) (5) (6) neglect the effects of flux saturation and leakage, but still provide a good 1^{st} order approximation of the actual relationships.

Eqn. (2) assumes that the valve and armature are not in contact with one another. This is done intentionally as we are only concerned with the release of armature while it is not in contact with the valve. If the release is done properly the armature and valve will move as a single mass through the remainder of the valve motion. The magnetic force generated by the lower magnetic coil is not included in Eqn. (2) as it has a negligible effect on the release.

3 Release of the Armature

Before proceeding with the design of the soft release controller let us first examine the physics and difficulties behind releasing the armature. Two procedures for releasing the armature are also presented in this section.

At the beginning of a valve opening/closing procedure the armature is initially held at rest against one of the two magnetic coils, where it remains until the magnetic force is reduced to less than the spring force. Once released, the motion of the armature generates current in the releasing magnetic coil retarding the motion of the armature. This adversely effects both the transition time and power consumption as a percentage of the potential energy stored in the spring will go toward generating electrical energy rather than kinetic energy.

The simplest method to initiate the armature motion is to zero the voltage difference across the magnetic coil. For a nominal holding current of 1 A it takes approximately 30 ms before the current discharges to a low enough level to initiate the armature motion as shown in Fig. 2. In addition, the armature motion generates up to 4.5 A of current.

A more efficient method is to apply the release suggested in [8] and shown in Fig. 3. The release of the armature is executed by applying the maximum negative voltage for a set duration. This quickly reduces the current to zero and effectively cancels the current generated by the armature motion.

Unfortunately, this method can lead to large impacts when valve lash is present. At maximum lash the armature accelerates up to 2 m/s before colliding with the valve, as seen in Fig. 4. A controller which is capable of releasing the armature quickly while avoiding large impacts is presented in the next section

4 Soft Release Controller

In order to achieve soft release of the armature, it is desired that its velocity be given by

$$v_{des} \leq 0.4\,\mathrm{m/s}. \tag{7}$$

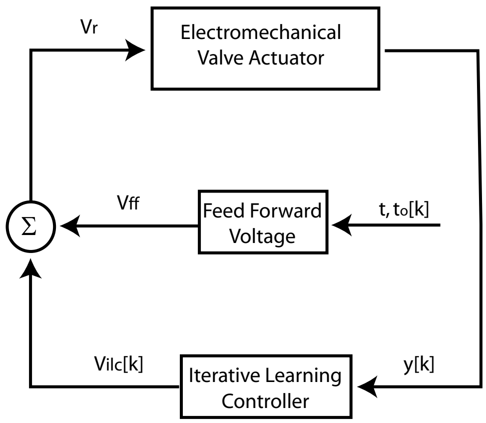

Figure 5. Block diagram of the soft release controller.

One of the simplest approaches is to achieve a linear position ramp (constant velocity) throughout the lash region, $0.5x10^{-3} \geq z \geq 0$. This is accomplished by designing a controller to track the position profile given by

$$z_{des} = 0.4\left(t - t_o\left[k\right]\right) \text{ for } 0.5x10^{-3} \geq z \geq 0, \tag{8}$$

where $t_o[k]$ is the time at which the armature motion is initiated at the k^{th} valve opening procedure. The armature motion is initiated by applying an open loop negative voltage to the magnetic coil to reduce the holding current. Once the armature begins to move at time $t_o[k]$ the open loop negative voltage is turned off and the tracking controller is turned on. The time at which the armature motion is initiated, $t_o[k]$, is determined by when the measured velocity exceeds 0.1 m/s.

Tracking of the profile is accomplished through the combination of feed forward and iterative learning control. The feed forward controller brings the system near the desired performance by applying the theoretical voltage which generates the current, i_{des}, corresponding to tracking of z_{des}. The iterative learning controller then compensates for modeling uncertainty by adjusting the applied voltage from one valve event to the next. The arrangement of the controller is shown in Fig 5. The total voltage command to the electromechanical valve actuator, V_r, is

$$V_r = V_{ff} + V_{ilc}, \tag{9}$$

where V_{ff} is the feed forward voltage and V_{ilc} is the additional voltage from the iterative learning controller.

4.1 Feed Forward Control

Feed forward control is advantageous as it utilizes the inherent system dynamics which may be beneficial for soft release, i.e. the current generated in the magnetic coil by the armature motion. The desired constant velocity ramp implies zero acceleration, which occurs when

$$F_{mag}\left(i_{des}, z_{des}\right) = k_s\left(l - z_{des}\right) + k_{pre} \tag{10}$$

if the effects of friction, which are small at low speed, are neglected. Solving for i_{des} we find

$$\frac{k_a i_{des}^2}{\left(k_b + z_{des}\right)^2} = k_s\left(l - z_{des}\right) + k_{pre} \tag{11}$$

$$k_a i_{des}^2 = \left(k_s\left(l - z_{des}\right) + k_{pre}\right)\left(k_b + z_{des}\right)^2 \tag{12}$$

$$\Rightarrow i_{des} = \sqrt{\frac{k_s\left(l - z_{des}\right) + k_{pre}}{k_a}}\left(k_b + z_{des}\right). \tag{13}$$

Differentiating Eqn. (13) with respect to time

$$\frac{di_{des}}{dt} = -\frac{1}{2}\left(\frac{k_s\left(l - z_{des}\right) + k_{pre}}{k_a}\right)^{\frac{-1}{2}} \frac{k_s v_{des}\left(k_b + z_{des}\right)}{k_a} + \sqrt{\frac{k_s\left(l - z_{des}\right) + k_{pre}}{k_a}} v_{des}.$$

Next, substituting Eqns. (4) (5) into Eqn. (3) the current dynamics can be rewritten as

$$\frac{di}{dt} = \left(\frac{\left(V_r - ri\right)\left(k_b + z\right)}{2k_a} + \frac{iv}{\left(k_b + z\right)}\right). \tag{14}$$

Replacing i, z , v, and V_r with i_{des}, z_{des}, v_{des}, and V_{ff} respectively, we can solve for the feed forward voltage

$$\frac{di_{des}}{dt} = \left(\frac{\left(V_{ff} - ri_{des}\right)\left(k_b + z_{des}\right)}{2k_a} + \frac{i_{des}v_{des}}{\left(k_b + z_{des}\right)}\right)$$

$$\Rightarrow V_{ff} = \left(\frac{di_{des}}{dt} - \frac{i_{des}v_{des}}{\left(k_b + z_{des}\right)}\right)\frac{2k_a}{k_b + z_{des}} + ri_{des}.$$

The feed forward voltage is therefore solely a function of time, which is easy to implement and eliminates the need for extra sensors. Due to modeling uncertainty and imperfections in the triggering time, feed forward control is not able to achieve perfect tracking alone. Therefore it is augmented with an iterative learning controller.

4.2 Iterative Learning Control

Iterative learning controllers (ILC) exploit the repetitive nature of a system to improve the tracking of a desired trajectory from cycle to cycle. Based on the tracking error of the previous iteration the ILC modifies the input of the next iteration in order to reduce the error. For our purposes the ILC compares the measured output of the armature with the desired trajectory given in Eqn. (8) after each valve event and then modifies the voltage of the next valve opening event to improve the tracking of Eqn. (8).

Before applying the ILC to the EVA, an overview and proof of the iterative learning controller used here is presented. First let us define

$y_d \in R^n$ as the discrete desired trajectory
$y[k] \in R^n$ as the discrete system output of the k^{th} iteration
$u[k] \in R^n$ as the discrete system input of the k^{th} iteration

The goal of the ILC is to determine the input u^* such that in the limit as the iteration number, k, tends toward infinity

$$\lim_{k\to\infty} u[k] = u^* \text{ and} \tag{15}$$
$$\lim_{k\to\infty} y[k] = y_d. \tag{16}$$

The mapping Γ which relates the input, $y[k]$, to the output, $u[k]$, is defined as

$$\Gamma := R^n \to R^n \text{ s.t. } y[k] = \Gamma(u[k]) \tag{17}$$

where

$$\exists u^* \text{ s.t. } y_d = \Gamma(u^*). \tag{18}$$

It is assumed that the nonlinear mapping Γ can be approximated by the linear mapping $P \in R^{n\times n}$ such that

$$y[k] \approx Pu[k] \text{ and } y_d \approx Pu^*. \tag{19}$$

Using the linear formulation of the iterative learning controller

$$u[k+1] = Su[k] + E(y_d - y[k]), \tag{20}$$

the matrices $S \in R^{n\times n}$ and $E \in R^{n\times n}$ must be chosen such that

$$\lim_{k\to\infty} u[k] = u^*. \tag{21}$$

Let us select the matrices S and E as

$$S = I \text{ and } E = \tfrac{1}{\sigma_o} RL^T \tag{22}$$

where R and L are the right and left singular vectors of the singular value decomposition, $P = L\Lambda R^T$. Λ is a diagonal matrix whose elements are the singular values, σ_i, of the matrix P, arranged in decreasing order, $\sigma_o \geq \sigma_1 \geq \cdots \geq \sigma_i \geq \cdots \sigma_{n-2} \geq \sigma_{n-1}$.

Substituting Eqn. (19) into Eqn. (20)

$$\begin{aligned} u[k+1] &= Su[k] + E(y_d - Pu[k]) \\ \Rightarrow R^T u[k+1] &= \left(I - \frac{1}{\sigma_o}\Lambda\right) R^T u[k] \\ &\quad + \frac{1}{\sigma_o} L^T y_d \end{aligned}$$

and applying the linear transformations

$$v[k] = R^T u[k] \text{ and} \tag{23}$$
$$\mu = L^T y_d \tag{24}$$

results in the de-coupled system

$$\begin{aligned} v[k+1] &= \left(I - \frac{1}{\sigma_o}\Lambda\right) v[k] + \frac{1}{\sigma_o}\mu \\ v[k] &= \left\{ v_o[k] \cdots v_{n-1}[k] \right\}^T. \end{aligned}$$

The dynamics of each element v_i can be written individually as

$$v_i[k+1] = \left(1 - \frac{\sigma_i}{\sigma_o}\right) v_i[k] + \frac{1}{\sigma_o}\mu_i \tag{25}$$

Solving explicitly for $v_i[k]$ results in

$$v_i[k] = \left(1 - \frac{\sigma_i}{\sigma_o}\right)^k v_i[0] + \frac{1 - \left(1 - \frac{\sigma_i}{\sigma_o}\right)^k}{\sigma_i}\mu_i \tag{26}$$

which converges to

$$v_i^* = \lim_{k\to\infty} v_i[k] = \frac{1}{\sigma_i}\mu_i. \tag{27}$$

Therefore output components which require small inputs are learned faster than output components requiring large inputs, since the convergence rate is determined by $1 - \frac{\sigma_i}{\sigma_o}$ and the required input, v_i^*, is proportional to σ_i^{-1}. This helps to avoid actuator saturation.

Transforming back into the coordinates y_d and u

$$R^T u^* = \Lambda^{-1} L^T y_d \tag{28}$$
$$u^* = R\Lambda^{-1} L^T y_d. \tag{29}$$

Substituting into Eqn (19) the plant output is

$$y = Pu^* \tag{30}$$
$$y = L\Lambda R^T u^* \tag{31}$$
$$y = L\Lambda R^T R\Lambda^{-1} L^T y_d \tag{32}$$
$$y = y_d \tag{33}$$

Therefore as the iteration number, k, tends toward infinity the plant output tends toward the desired trajectory y_d. It is important to note that the ILC is not simply inverting the plant. Recall that the mapping P is only an approximation of the input to output characteristics of the system. The ILC uses the tracking error at each iteration to determine the true relationship between the input and output in order to achieve the desired tracking.

In order to guarantee tracking of Eqn. (8) by the armature we define

$y[k] \in R^n$ as the discrete response of the state z between $0 \leq z \leq 0.5$.
$u[k] \in R^n$ as the additional voltage, V_{ilc}, added to the feed forward voltage, V_{ff}.

The discrete desired trajectory

$$y_d = \left[y_{d0}, y_{d1}, \cdots, y_{di}, \cdots, y_{d(n-1)}\right] \tag{34}$$

is defined as

$$y_{di} = 400 i \Delta T, \tag{35}$$

and the linear mapping, P, is a square $n \times n$ matrix given by

$$P = \begin{bmatrix} h[0] & 0 & 0 & \cdots & 0 \\ h[1] & h[0] & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & & \vdots \\ h[n-2] & h[n-3] & \cdots & h[0] & 0 \\ h[n-1] & h[n-2] & \cdots & h[1] & h[0] \end{bmatrix}$$

where $h[j]$ is the j^{th} element of the discrete impulse response of the discrete linear model obtained from linearizing at $z = 0.5$ mm and discretizing at 20 kHz.

5 Experimental Setup and Results

The controller outlined in Sec. 4 is implemented using a laser vibrometer to measure the position and velocity of the armature during the valve release. This signal is then sampled by an 1103 dSpace processing board at 20kHz. Based on the control algorithm and the measured armature position the dSpace processing board regulates the voltage to a set of current drivers in order to achieve the desired performance.

The response of the 1^{st} and 13^{th} iteration are shown in Figs. 6 and 7 respectively. The first iteration shown in Fig. 6 is the response of the system using only the feed forward controller. While an improvement over the release proposed in [8], see Fig. 4, perfect tracking is not achieved and the armature and valve collide at approximately 1 m/s. Thirteen valve events later, Fig. 7, the iterative learning controller has improved the tracking significantly and the armature and valve collide at approximately 0.4 m/s.

6 Summary and Conclusion

Valve lash plays a critical role in the operation of the electromechanical valve actuator. While necessary for the thermal expansion of the valve, it creates the potential for large impacts. This paper has presented an iterative learning controller which is capable of bounding these impacts by 0.4 m/s through trajectory

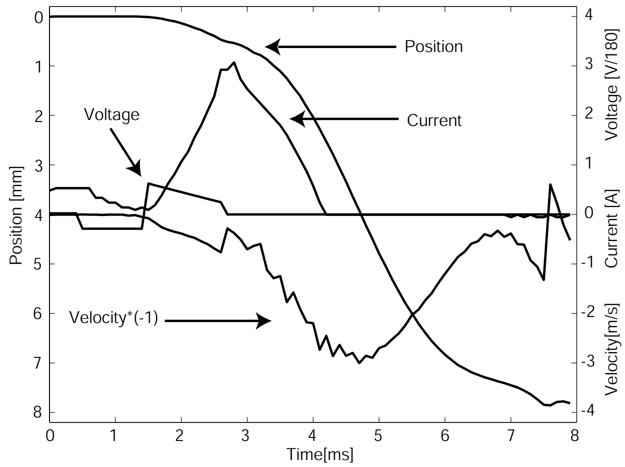

Figure 6. 1^{st} Iteration (i.e. feed forward only).

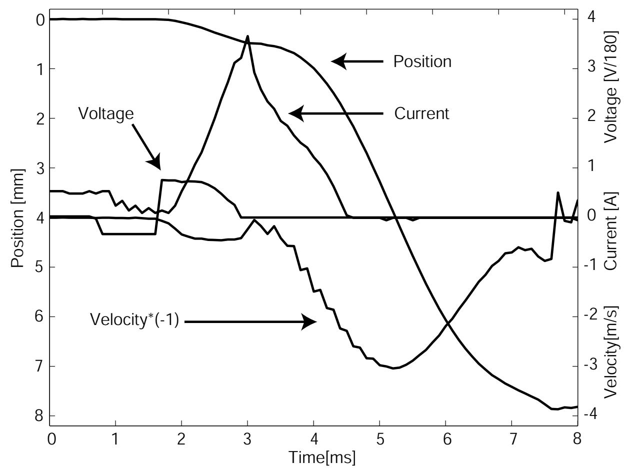

Figure 7. 13^{th} Iteration.

tracking. The use of control theory to exploit the existing hardware is advantageous compared to a physical lash adjuster which would increase both cost and packaging size.

The controller still requires more work before it can be implemented in a production vehicle. During operation in an engine the valve lash will fluctuate due to the expansion and contraction of the valve. The controller must therefore be able to somehow estimate the valve lash and/or account for changes in it. In addition, another method must be found to determine the initiation of motion as the precision of the position sensor is inadequate and it is not feasible to use a measurement of the velocity. A logical approach would be to apply a closed loop controller to initiate the motion.

While soft release is important it represents only a portion of the impacts which can occur in the electromechanical valve actuator. Future work will concentrate on integrating the soft release controller presented here with a soft landing controller in order to reduce all of the impacts which can occur during the operation of the electromechanical valve actuator.

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