

Direct Fuel Injector Power Drive System Optimization

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ABSTRACT

The objective of this study is to optimize the injector power drive system for improved fuel injection quantity and timing control. The power drive system was optimized for improved injection repeatability under different operating conditions such as fuel supply pressures. A coupled simulation of injector electromagnetic, pintle (needle) rigid body motion and computational fluid dynamics (CFD) model was employed to generate the optimal values of the 1st stage current, the 1st stage on-time and the 2nd stage current. The simulation results were validated against the experimental data measured with a photo detector measurement system.

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INTRODUCTION

Direct fuel injectors have rapidly replaced carburetors and manifold fuel injectors in modern internal combustion (IC) engines. With a direct fuel injection system, high-pressure fuel is directly sprayed into a combustion chamber. The most common fuel injector actuator is a solenoid type, which converts electrical energy into mechanical motion through electromagnetics. A pintle valve inside the injector is used to electronically control the opening and closing of the nozzle. The motion of the pintle (needle), which acts as a plunger in the solenoid, defines the temporal characteristics of a spray, i.e. opening delay time, closing delay time, spray duration and its rate shape. These temporal spray characteristics are important parameters in an Engine Control Unit (ECU), which contains tables with injection timing and duration for optimal combustion and emission control under different engine operating conditions. The ECU determines required injection duration per requested fuel injection quantity from the injection duration table. Then, the ECU sends a control signal to the fuel injection power module, which sends a current signal to the injector solenoid coil to create magnetic field in the stator. Then, the stator pulls the pintle to open the injector nozzle.

This pintle movement occurs when the magnetic force overcomes the opposing forces, i.e. pressure, spring compression and pintle valve contact friction forces.

The physics involved in the fuel injector pintle movement is a complex combination of electromagnetic, fluid dynamics and coupled motion with pintle and valve structures where the injector power drive system plays a key role in the dynamics of the pintle. Desired pintle dynamics should have the following characteristics: (1) fast response, (2) repeatability, and (3) least power consumption.

Fast response implies short opening and closing delay times which are critical in modern IC engines because fuel injection should be made at optimal timing in narrow window. Combustion is optimized when fuel is injected at optimal timing at each operating condition. Optimal injection timing is determined for best combinations of engine performance, efficiency and emissions, considering fuel-air mixing time, ignition delay time and dwell time. Dwell time is defined as the time between the end of injection and the start of combustion. In modern compression-ignition direct injection (CIDI) engines, injection timing ranges from several degrees before to near top dead center (TDC) depending on the engine operating

conditions. Injection timing is typically retarded as engine load is increased. Pilot injection strategies have been widely used to reduce combustion noise and improve engine idling. Typical pilot injection quantities range from about 1 to 5 mg for advanced diesel engines. Fast pintle movement is critical in multiple injections because multiple injections should be made in each cycle, while the first injection minimally influencing the following injection. Increasing the current ramp rate of the solenoid coil would increase the pulling motion of the pintle, given that in theory the magnetic force is proportional to the square of supply current to the injector. In reality, however, it will reach a point where increasing the magnetic force rate is impeded by the limited current increasing rate, which is determined by inductance. Other factors such as hydraulic hysteresis, magnetization hysteresis and saturation of the magnetic material also impose limitations on pintle response time.

Repeatable fuel injection leads to less shot-to-shot variations of fuel injection quantity and injection rate. Repeatable fuel injection can be achieved when the pintle moves rapidly to a desired position (typically fully open position) to avoid random fuel injection quantity and rate. Higher current may ensure the repeatability of the injection by creating more than enough magnetic force to hold the pintle at its desired position.

However, higher current would create more heat in the solenoid coil, which increases the temperature of the surrounding magnetic material, thus degrading the magnetic material property, i.e. lowered saturation limit and more hysteresis. Injector performance is highly dependent on temperature in the solenoid which was observed during our injector dry test in which the threshold current increased significantly as the injector body temperature was increased. Ideally, an injector power drive system should use the least amount of current, while achieving fast response and repeatable pintle movement.

In the past, research has been performed mostly in two different areas: (1) numerical modeling of fuel injector dynamics and (2) power drive design for direct fuel injectors that typically deal with power strategies to the injector solenoid coil. Numerical simulation codes for diesel injection systems were developed by various authors [1, 3, 4]. All these codes include or partially include coupled multi-physics model of hydraulics, fluid, mechanical and electromagnetic. Digesu's model coupled one-dimensional hydraulics with a two-dimensional (2D) axisymmetric electromagnetic finite element code to provide magnetic force in terms of exciting current and working gap [1]. In his study, needle lift, pressures (pipes, control volume, rail and accumulative volume) and flow rate were matched with experimental data. The authors investigated how pipe design affects the needle lift profile due to the hydraulic wave, and showed a moderate dependence on pipe parameters. Ficarella developed a code to evaluate the instability phenomena in a common rail injection system to predict injection characteristics [2]. It was found that the most challenging part of the modeling lies in the control valve whose

residual motion causes re-opening of the valve after a pilot injection. Coppo's code was also based on a common-rail injector with a combined pipe, fluid, mechanical and electromagnetic model [3, 4]. Experimentally measured exciting current signals were input into the model, which included magnetic saturation effects. Good agreement was observed between calculated and experimental profiles of rail pressure, needle lift, and injection quantity. Hu developed a one-dimensional (1D) model to correlate the pressure profile with the measured one in which no electromagnetic model was used and a measured magnetic force profile was employed in the 1D model [5]. Ando developed a 1D electromagnetic model coupled with simplified rigid body and fluid models [6]. The main emphasis of this model was on the electromagnetic effects including magnetization time lag.

For power drive optimization, Tsai designed a three-stage electrical drive for high-pressure gasoline direct injection (GDI) injectors. In the design, the first two stages used a power Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) to switch between power supplies, while the 3rd stage used pulse-width-modulation (PWM) control. The author provided the current amperages for each stage (12/5/3A) but did not fully explain why those values were chosen. The author observed that the pintle closed faster with the 3rd stage PWM control than with a direct voltage control method [7]. Tsai, in another paper, performed a parametric study to investigate the effect of voltage, current, frequency and fuel pressure on injection quantity [8].

From the literature review, it was found that there is a lack of integral method to model from injector power source to pintle dynamics, as well as driver design details for controlling fuel injectors. The goal of this paper is to find the optimal power strategy to drive fuel injectors, specifically in our case, it is a gasoline direct fuel injector (GDFI). The methodology of fulfilling this goal is as follows: using electromagnetic-mechanical-fluid coupled simulation to reveal the impact of injector current shapes on injection dynamics, as well as to achieve fast response and repeatability of pintle movement with the least power consumption or the minimal driving current. Through fluid and mechanical model, the electromagnetic force requirement is formed; and through electromagnetic circuit analysis, the corresponding current requirement, which contains optimal parameters for multi-stage current shape, is established under different supply pressures. Finally, the simulation results are validated using a photo detector system.

The paper is organized as follows: Firstly, injector power drive system basics, electromagnetic system, mechanical system and fluid system are introduced separately in four different sections. These four sections are the building blocks for the entire system. Secondly, a coupled simulation is run using one of the power strategies (current shapes) to reveal the detailed dynamics of pintle movement, flow rate and pressure forces on the pintle under different supply pressures. The insight of current requirement is gained after this run of simulation.

Thirdly, two more power strategies (current shapes) are applied to illustrate the failure of maintaining the injection repeatability if the current requirement is violated. Fourthly, the optimal power strategy is discussed in detail, which includes the reason of using the multi-stage current shape and its optimal parameter settings. Lastly, the simulation results are validated using a photo detector system.

Injector Power Drive System Basics

Direct fuel injectors are designed for fast response under high pressures, which requires careful selection of their power drives. The power input to the injector coil creates a magnetic force to open the pintle valve. Since magnetic force is proportional to the square of supply current, the pintle will only move when supply current reaches certain levels where magnetic force overcomes opposing forces (including pressure, spring and friction forces). The threshold of the pintle movement depends on the threshold level of the excitation current in the solenoid coil. Therefore, how fast the pintle opens depends on how fast the current level can reach the required current threshold. However, there is always a time constant for current rise due to the inductance in the solenoid coil. The current rising rate needs to be fast to achieve fast opening of the pintle.

The governing equation for a simple resistor-inductor circuit (RL circuit) is

$$V = i \cdot R + L \cdot \frac{di}{dt} \quad (1)$$

where V is the voltage across the coil; R is the resistance; and L is the inductance. The step voltage input response of the current is obtained by solving (1) to obtain:

$$i(t) = \frac{V}{R} \cdot (1 - e^{-\frac{R}{L}t}) = \frac{V}{R} \cdot (1 - e^{-\frac{t}{\tau}}) \quad (2)$$

where $\frac{L}{R}$ is the electrical subsystem time constant τ . The inductance was measured to be 1.9 millihenry (mH) at 1 kHz and 3.9 mH at 0.12 kHz at the maximum air gap. In our case,

$$\tau = \frac{L}{R} = \frac{(1.9 \sim 3.9)mH}{1.5\Omega} = 1.26 \sim 2.6ms \quad (3)$$

This means that it takes 1.26~2.6 ms to reach 63.2% of the $\frac{V}{R}$ steady-state current $\frac{V}{R}$; where R , L are measured values.

Figure 1 illustrates the times to reach 8.5 A for different voltage inputs. The reason for 8.5 A in the analysis will be discussed in the later section where the magnetic force requirement is specified.

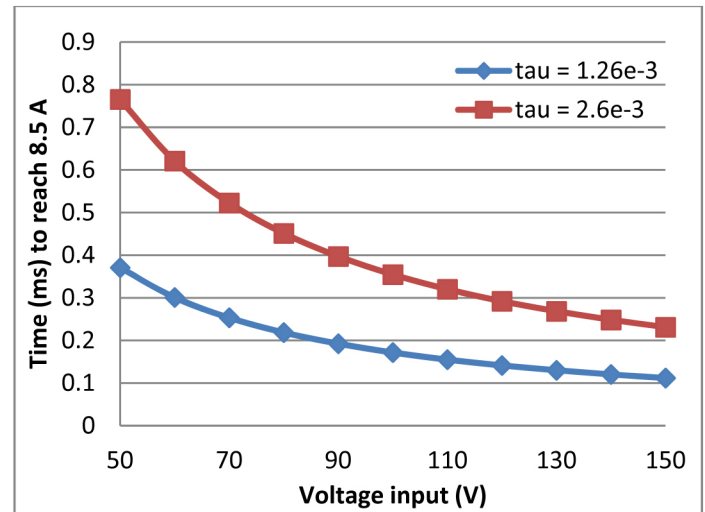


Figure 1. Time to reach 8.5 A with different time constants

A PWM servo-power amplifier was used to provide current to the fuel injectors. Nowadays, PWM amplifiers become the preferred way of driving fuel injectors. Compared with power MOSFETs, PWM power amplifiers are more power efficient and easier to use.

A PWM power amplifier consists of a DC power supply, capacitor (for short pulsation application), and control signal. The DC power supply delivers power to the PWM via the capacitor. Through the PWM frequency and duty cycle, the output current (or voltage) is modulated to match the input control signal shape at higher power level. For instance, in our system, 0~10 volts control signal was fed into PWM and the output from the PWM was 0~15 A current shape that closely followed the input control signal. This approach is extremely helpful because real applications utilize complex control strategies of the fuel injectors. One of the main benefits of a PWM amplifier is that one can easily adjust the control signal amplitude and time duration with multiple stages to regulate the multiple stage current output to the fuel injector. Another benefit of the PWM control was discussed in Tsai's paper [Z] which showed that the last stage PWM control could shorten the closing delay time of the fuel injector pintle. Figure 2 illustrates the injector power and control system utilized in the present paper.

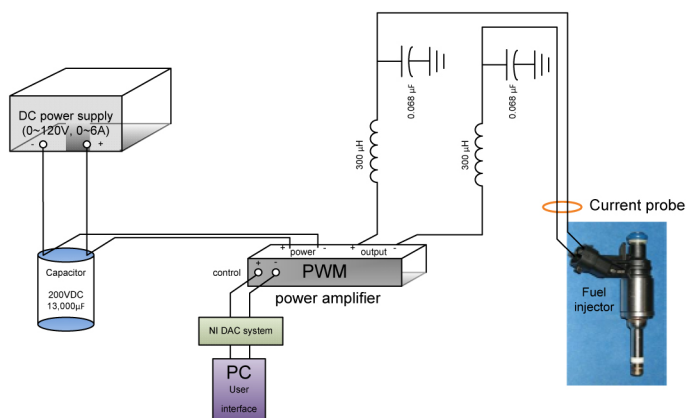


Figure 2. Injector power and control system

Electromagnetic System

Electromagnetic analysis is an essential part of the multi-physics model. The fuel injector used in this study is a BOSCH GDI injector (HDEV 5.2), which is a plunger type solenoid electromagnetic device. A coil is imbedded inside the injector body, with a magnetic conducting material forming a closed magnetic path when the coil is energized. The motion of the pintle is caused by the magnetic field created by the current flowing in the coil.

The electromagnetic model includes an electrical circuit model for the injector coil and a magnetic model for magnetic flux and force calculation.

The electrical circuit for the injector coil is basically a RL circuit. The PWM power amplifier was not modeled in this study due to the circuit's low frequency nature compared to the switching frequency of PWM, which is 22 kHz in our case. For direct comparison, the time constant of the injector RL circuit is about 2 ms, while the switching time is only 0.02 ms. Thus, the model was simplified to use three power sources: one voltage source with a time-controlled switch, together with two pulse current sources, to obtain a two-stage current shape. In the actual system, a two-stage control voltage signal is fed into the PWM power amplifier and then the output is a two-stage current shape. The electrical properties of the fuel injector coil and PWM power amplifier are listed in [Table 1](#).

The electrical circuit was modeled in Maxwell circuit editor, as shown in [Figure 3](#). It included a voltage source with a switch controlling on and off time, a pulse current source for the peak current, and another pulse current source for the holding current. This circuit model was imported into a 2D axisymmetric finite element code Maxwell as external excitation source for the coil. The time constant τ in the RL circuit (see [equation 3](#)) determines the maximum current increasing rate. The inductance, which is represented as winding1 in the circuit, changes as the geometry changes, which takes into account of the pintle motion in the magnetic circuit. [Figure 4](#) shows the inductance profile with respect to the change of air gap. The inductance from Maxwell was calculated through the

relationship $L = \frac{d\lambda}{di}$ at each time step in the transient analysis. It is shown that the change of the inductance due to pintle motion counts for about 10% of coil's total inductance.

Table 1. Electrical properties of the fuel injector coil and PWM power amplifier used in this study

Resistance		1.5 Ω
Inductance		1.9 mH at 1 kHz; 3.9 mH at 0.12 kHz
Number of turns		160
PWM switching frequency		22 kHz
PWM power range	Peak current	50 A
	Continuous current	25 A
	Supply voltage	40-190 VDC

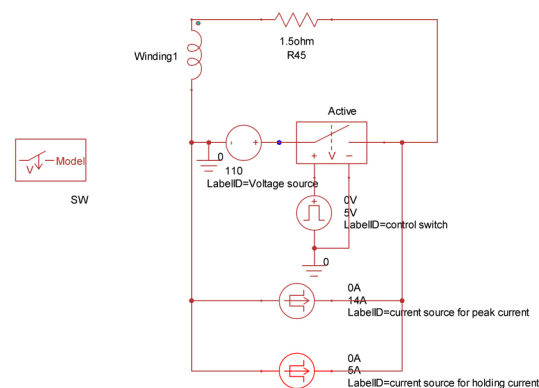


Figure 3. Electrical circuit in Maxwell circuit editor.

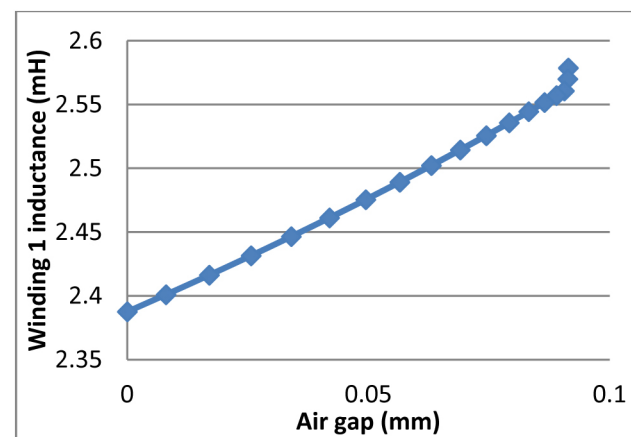


Figure 4. Inductance at different air gaps from Maxwell.

This inductance plays an important role in determining the current rise time. A 1D magnetic analysis is provided below to compare with the inductance calculation from Maxwell.

From Ampere's law $\oint_c \vec{H} \times d\vec{l} = I_{net}$

$$H_1 \cdot \Delta x + H_2 \cdot w + H_3 \cdot w = N \cdot I$$

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where, the parameters in Equation (4) are illustrated in Figure 5.

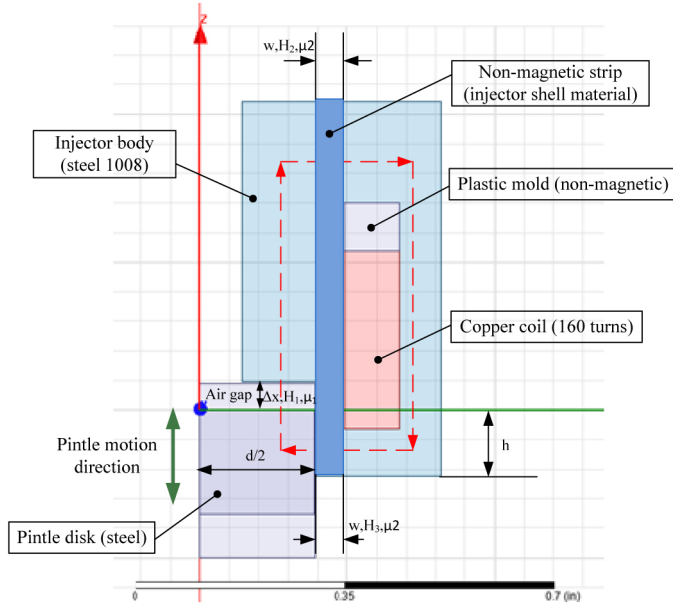


Figure 5. Flux path in the magnetic circuit analysis

Apply Gauss M around pintle disk, $\oint_s \vec{B} \times d\vec{a} = 0$

which yields

$$\mu_1 \cdot H_1 \cdot \frac{\pi}{4} d^2 - \mu_2 \cdot H_3 \cdot \pi d \cdot h = 0$$

(5)

Assume no fringing and leakage,

$$H_2 \cong H_3$$

(6)

Also, the permeability in the air μ_1 and the one in the non-magnetic strip μ_2 are similar: $\mu_1 \cong \mu_2$;

Apply flux linkage $\lambda = N \cdot \int_s \vec{B} \times d\vec{a}$ on the top plane of the pintle disk,

$$\lambda = \left[\frac{N^2 \cdot \mu_1 \cdot \frac{\pi}{4} \cdot d^2 \cdot h}{\frac{d \cdot w}{2} + \Delta x \cdot h} \right] \cdot i$$

(7)

$$L = \frac{N^2 \cdot \mu_1 \cdot \frac{\pi}{4} \cdot d^2 \cdot h}{\frac{d \cdot w}{2} + \Delta x \cdot h}$$

where, inductance

The geometric parameters were obtained by measuring the dimensions with a cut-open injector. Table 2 lists the parameters used in the calculation. The calculated inductance (2.4 ~ 2.6 mH) correlates well with the measured inductance, which ranged from 1.9 mH at 1 kHz to 3.9 mH at 0.12 kHz.

Table 2. Parameters for inductance calculation

Non-magnetic strip width w [mm]	0.8
Pintle disk diameter d [mm]	10
Pintle height h [mm]	4
Air gap Δx [mm]	0 ~ 0.1
Permeability μ_1 [H/m]	1.256e-6
Number of coil turns	160
Calculated inductance using eqn (7) [mH]	2.4 ~ 2.6

Figure 6 shows elapsed times for different current targets at the calculated inductances with the same 110 V voltage source using Equation (2).

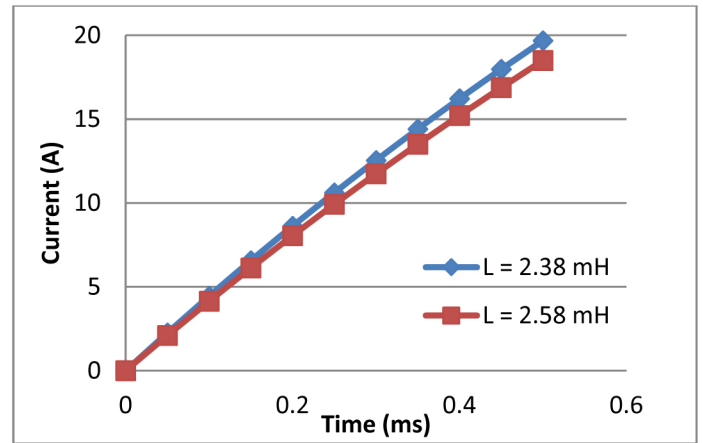


Figure 6. Current level vs. elapsed times at the calculated inductances

Figure 7 compares the calculated current shape from Maxwell and the measured one with the 1st stage on-time of 400 μs and 2nd stage on-time of 600 μs. The calculated current profile, especially the rise time (which is the key to the opening delay time), fits well with the measured current.

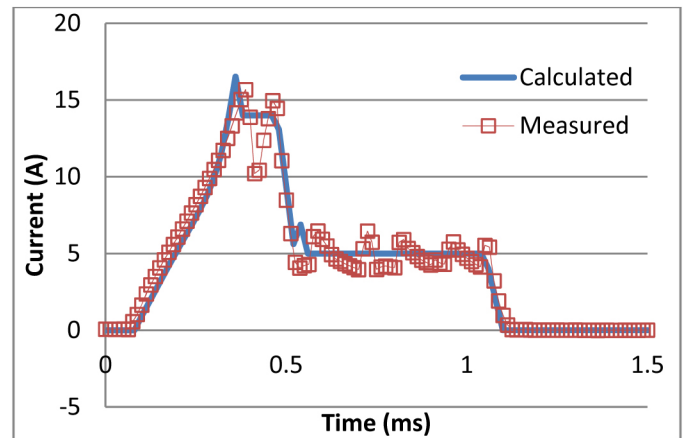


Figure 7. Maxwell calculated and measured current shapes

In the electrical circuit simulation, the current limit was set by the PWM power amplifier and the voltage source was turned off when the current reached the current limit. This was done to capture the characteristics of the rising curve and the current limit. Another pulse current source was used to provide the 2nd stage current. In practice, once a desired current shape is determined, it is relatively easy to adjust the current magnitude and duration by changing the DC power supply voltage, control signal amplitude, current limit and command signal's time durations.

In Figure 8, the 2D axisymmetric model in Maxwell shown in Figure 5 was simulated in transient. Magnetic density B vector plot was shown at time $t = 0.4$ ms at which the 1st stage current reached its steady-state.

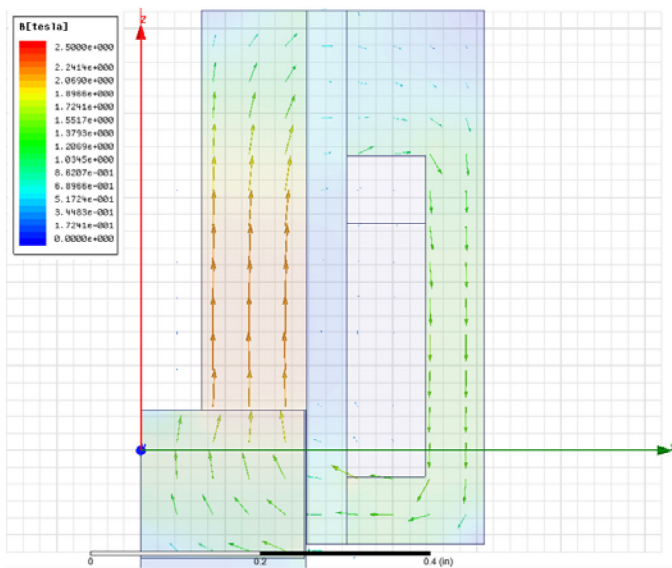


Figure 8. Magnetic flux density vector plot at $t = 0.4$ ms from 2D Maxwell transient with the two-stage current shown in Figure 7

The magnetic field density was calculated using the ampere's law and the constitutive relationship between flux density B and magnetic field strength H: $B = \mu \cdot H$. Then, Maxwell force law was used to calculate the magnetic force, given the magnetic flux density, permeability and area.

$$F_{mag} = \frac{B^2 A}{2\mu} = \frac{(\mu \cdot H_1)^2 A}{2\mu} \quad (8)$$

where, B is the flux density at H_1 ; A is the area on the upper surface of pintle disk; μ is the permeability of air.

Solving Equations (4, 5, 6) for H_1 , then substituting H_1 into Equation (8), the magnetic force becomes

$$F_{mag} = \frac{\mu \cdot N^2 \cdot h^2 \cdot A}{2\left(\frac{d \cdot w}{2} + \Delta x \cdot h\right)^2} \cdot i^2 \quad (9)$$

The magnetic force was also calculated using the finite element code Maxwell. Figure 9 compares the magnetic forces calculated with Equation (9) and Maxwell at different air gaps and current levels.

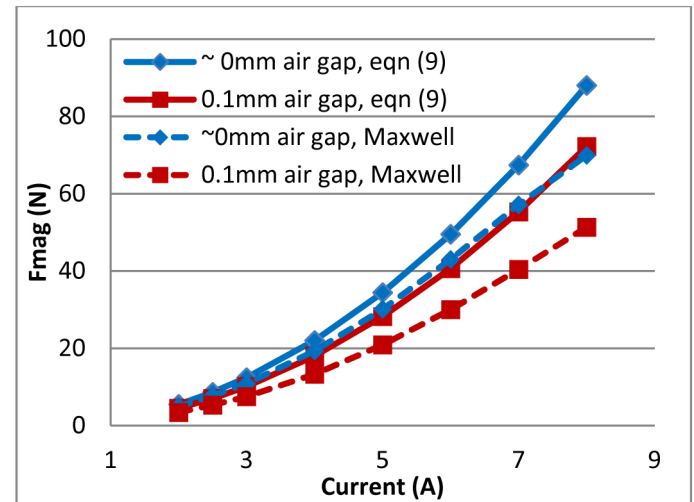


Figure 9. Calculated magnetic forces at different air gaps and current levels with Equation (9) and Maxwell

The 2D axisymmetric finite element code Maxwell considered the non-linearity of the B-H curve of the magnetic material and the fringing loss. Therefore, the magnetic force calculated using Maxwell was less than the theoretical force calculated from Equation (9) as excitation current increased. However, the two force curves are close enough to justify the results from Maxwell.

Figure 9 shows the magnetic forces calculated using finite element code Maxwell with the current shape shown in Figure 7 under three different conditions: with pintle motion and without pintle motion at extreme pintle positions.

Figure 10 shows that the magnetic force with moving pintle (solid) falls in-between the magnetic forces at extreme pintle positions without pintle motion (dotted and dashed). For simplicity, the magnetic force with non-moving pintle at its minimum air gap (~ 0 mm) was used in the following coupled analysis assuming that the magnetic force is only a function of time given a certain current shape.