Force-current relationship important when using linear motion for part production

Accuracy and precision of machine axis movement is paramount in achieving the tolerances and surface finishes required in today's part-production environment. Final part dimensioning, surface finishing, and mill cutters sharpening is often only possible through grinding operations. Grinding is a demanding machining operation that involves significant vibration, heat generation and abrasive particle creation, while needing to maintain positional and speed accuracy of the movement. Selection of the axis translation mechanism will determine the level of accuracy possible along with the cost of machine ownership.

A basic need of the machine design is to be able to go to a position, and knowing where that position is relative to the workpiece. In looking at achieving accuracy in the movement of a workpiece or the tooling, there are three areas of the machine design: the mechanical components, the command and control of the movement (control boards and servo loop), and the translation mechanism (linear motor or rotary motor and ball screw). This article is focused on one aspect of translation, specifically the force generated by linear electric motors.

Newton's first law tells us that, to alter its motion, an object requires to be acted upon by a force, F=ma. From this we know that we need to apply a force of a certain magnitude based on the mass of our object of interest and any resistive forces to put it on the necessary path to be shaped, honed, or ground to specification. We have to have accuracy and precision of the force vectors applied, and when we apply a force it needs to be exactly how much we want every time. This is just to get it where we want it, when we want it, not taking into consideration work hardening, elastic and inelastic deformation, tool deflection, or any other things important to production.

From a linear electric motor standpoint, motion is the interaction between an electromagnetic field created by current-carrying coils and permanent magnets. In creating motion, we know that we need to generate a force to do so. For electric motors, this requires that a current be supplied to create a magnetic field. When opposite polarity fields of the electro and permanent magnets are aligned, the motor will be stationary, and when they are offset, a force will be generated and movement can occur. The force generated is directly related to the current magnitude in the coils, as the current determines the magnetic field size, and this determines the force created. In a very real sense the magnitude, timing, and direction of the current is one of the more important control inputs for creating any given motion profile with electric motors. The relationship between the current and motor performance lays the foundation for how motion commands are executed via the motor. If 20N of force are needed to move to position (x,y), I need to know how much current to supply. Ideally, the force (F)-current (I) relationship (F (I)) is linear, so that a small change in current gives a similar small change in force throughout the entire range of operation. Difficulties can arise when the relationship is non-linear or has a non-linear regime such that large changes in current are required to get smaller changes in force. Graphical schematics of the F(I) relationships for two motor types are shown in Figure 1. Motors with these non-linear regimes require advanced servo loop systems to account for the changing force outputs for the current in the non-linear regime.

Potential Applications:

Why would a motor have a non-linear F(I) relationship? The electromagnetic fields are manipulated to create and control the motion of the motor. This changing magnetic field induces current flow in magnetically susceptible conductive materials in the same way current flow in a conductor creates a magnetic field. These are called eddy currents. The electromagnetic coils in some motor types induce eddy currents in other motor parts. The eddy currents then create an additional magnetic field. Since magnetic fields are a vector quantity, the direction and magnitude of the all the interacting fields are important, as they sum up over space, affecting the overall force generated by reducing the field strength between the primary magnetic components. As current is increased to generate more motor force, the eddy currents and their magnetic fields grow. This effect produces a non-linear F(I) relationship in iron core type linear motors. When any large amount of a conductive material moves in relation to a magnetic fields eddy currents will be produced. The presence of necessary heat sinks on ironless linear motors also creates non-linear affects in F(I) due to the eddy currents generated by the interacting magnetic fields and heat sink. Some basic design efforts for the motors help reduce – but will not eliminate – eddy currents.

Why the Nippon Pulse Linear Shaft Motor has a linear force-current relationship

The basic structure of Nippon Pulse's Linear Shaft Motor eliminates the generation of eddy currents that will cause the F (I) relationship to be non-linear. In order to understand why this is the case, here is some background on how magnetic fields create large or small eddy currents. Each material type has a certain amount of susceptibility to magnetic field-created eddy currents. For magnetic fields with low frequency of change, the main differentiator of materials is the conductivity. When the frequency of the fields increases, the magnetic permeability of the material also becomes important. This is reflected in the depth of penetration of the magnetic field into the material, known as the skin depth.

When the magnetic field creates an eddy current within a metal, energy is consumed through the resistive heating of the metal and by the creation of the eddy current magnetic fields and their effect on the primary magnetic field. Power dissipation of the eddy currents per unit volume is generally given by the equation:

$$P = \frac{\pi^2 \sigma B_P^2 d^2 f^2}{6\delta} \qquad (1)$$

Where σ is the material conductivity, B_p is the peak magnetic field, d is the thickness of the material or laminations, f is the frequency of the field switching, and δ is the material density. From the equation, you can see that to reduce power dissipation, reducing material thickness and conductivity while increasing material density will reduce power consumption for a given magnetic field strength and frequency. If the frequency of the field is high enough, the magnetic permeability of the material becomes important, as the change in the field direction is fast enough that the magnetic field doesn't penetrate all the way through the material before switching directions. This creates a skin effect, where the magnetic field only penetrates so far into the metal. The depth of penetration is a new effective depth in calculating the power dissipation. Calculation of the skin depth is given by:

$$S = \frac{1}{\sqrt{\pi f \sigma \mu_r \mu_0}} \qquad (2)$$

With μ_r being the relative magnetic permeability of the material and μ_0 is the permeability of a vacuum. In this equation, it is shown that as μ_r and σ increase, the skin depth decreases. Therefore, high conductivity and high permeability materials are ideal for use around magnetic fields.

In looking at the power dissipation, the relevant component to this discussion on the force vs. current relationship is the magnetic field in equation 1. As the magnetic field increases the power dissipation increases as the second power of the field intensity magnitude. The coil generated magnetic field that generates the eddy current is given by:

$$B = \mu_r \mu_0 n I \qquad (3)$$

Where n is the turn density of the coil and I is the current. As equation 3 illustrates, the magnetic field intensity is linearly related to the current. In iron core motors, μ_r is the relative permeability of the iron composition used as the core. For those motors, the core is necessary to create a larger magnetic field over that of an air core coil since the design utilizes half of the magnetic flux of the permanent magnets.

Next, we should look at the force generated by coil interacting with a permanent magnetic field. The force between the magnetic field generated by the coil and a permanent magnet is (in a general sense):

$$F = \mu_0 n I B Sin\theta \qquad (4)$$

For permanent magnet motors the magnets are laid out so that only one pole interacts with the magnetic field of a coil at any given time. It's this relationship that creates the linear force. If both poles interacted, rotational torque would be created. The force equation shows that the force-current relationship is linear for a given angle orientation between the field direction of the coil and field direction of the permanent magnet. Maximal force is generated when the field lines cut each other at 90 degrees.

Nippon Pulse motors have a linear F(I) relationship because the motors do not have a significant amount of conductive material surrounding or adjacent to the electromagnetic coils. For other motors that have this material, there is the counteracting magnetic field and power dissipation through resistive heating (I^2R). We can see this in a qualitative sense by looking at the influence of equations 1, 3, and 4. We know that the current and created magnetic field in the coils is linear, as is the current-force relationship, but the power dissipation of the eddy currents is not. When you have enough material to interact with the motor's magnetic field, power dissipation becomes important at higher currents (magnetic field strengths) due to the non-linear power dissipation relationship. For an electric motor, power put into the motor is current time voltage (P=IV), and power dissipated is typical due to the resistive heating loss, or I^2R. When you consider eddy currents, energy is used to generate current and magnetic fields in the conductive material. This energy is not used to generate force between the coils and permanent magnets. This non useful power dissipation grows as the square of the magnetic field and will have a greater negative impact on the production of force at higher currents. This is the origin of the non-linear relationship seen in iron-core and core-less with heat sinks at higher force outputs.

There is not a significant amount of conductive material surrounding or in the magnetic coils (iron core motors) or external heat sinks (core-less motors) to keep the motor cool enough to operate. The Linear Shaft Motor has a permanent magnet shaft with a high intensity magnetic field with a small spatial distribution at each pole. The symmetry of the electro-magnetic coils about the shaft and the field properties of the permanent magnets generates significant force without the need for an iron core to enhance the magnetic field produced by the coils. Temperature of operation of the Linear Shaft Motor is 135°C without any loss of produced force or motor stiffness due to the motor design, unlike core-less motors, where increased heat causes separation or movement of the permanent magnets from their fixed locations.

<u>Conclusion:</u>

In utilizing a motor, knowing what you get out for what you put in is important. The simpler that you can make it, the more elegant and robust your system will be. With a linear force-current relationship, you don't need to accommodate non-linear effects through approximation or additional terms to the F(I) equation. This in turn will improve accuracy and repeatability as the force produced is the force requested every time. Nippon Pulse has developed an efficient Linear Shaft Motor that has an exceptionally linear F(I) relationship, so it does what you want with no need for advanced servo control.

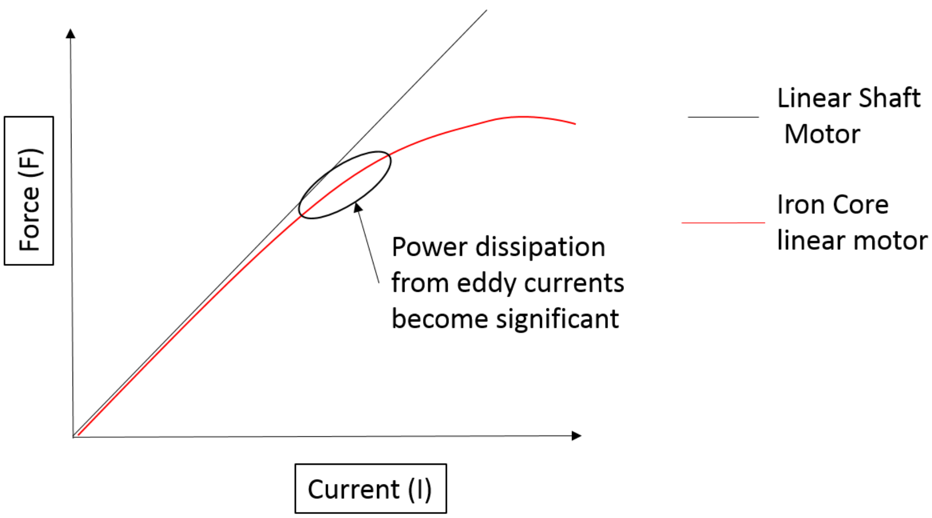

Figure 1. Graphical representation of F(I) for two electric linear motor types.