DESIGN OF A RELUCTANCE ACCELERATOR

D. A. Bresie and J. A. Andrews

Presented at the
5th Symposium on Electromagnetic
Launch Technology
Eglin AFB, Florida
April 2-5, 1990

Publication No. PR-107
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512) 471-4496
DESIGN OF A RELUCTANCE ACCELERATOR

D.A. Bresie and J.A. Andrews

Center for Electromechanics
The University of Texas at Austin
10100 Burnet Road, Bldg. 133
Austin, TX 78758-4497

Abstract: Linear electromagnetic accelerators have many potential uses, "in space or at-sea" and industrial applications. Many of these uses require that the accelerator be exposed to hostile environments such as might be found in space or underwater. One type of accelerator, the reluctance accelerator, has advantages in these hostile environments because its armature operates without sliding contacts or flexible cables. This device has electrical turns only in the stator. The armature consists of one or more slugs of ferromagnetic material. The reluctance accelerator exhibits the same good controllability as synchronous accelerators. They have seen little use, however, because they are relatively difficult to design.

This paper describes the design of a reluctance accelerator and discusses the methods used in its design. It also discusses the methods of control of the accelerator and its predicted performance. Because this device contains iron and is therefore very nonlinear, it was necessary to employ a finite element (FEA) code (TEXMAP) in order to determine the forces developed by the accelerator and to determine the inductance of the windings at various stroke positions.

Results of the analysis show that the true performance of a reluctance launcher varies considerably from that predicted by classical closed form flux analysis. This paper shows that although the reluctance accelerator has some limitations in maximum force for a given bore area, predicted efficiency is relatively good when compared with air-core induction machines.

Introduction

Linear motors can be classified in the same types as their rotary counterparts. They are used in many applications and their performance is well understood. However, use of a linear motor as an accelerator has been less widespread. The reason is that the introduction of transients caused by acceleration makes the design more difficult.

Survey of Art

Engineers at the Center for Electromechanics at The University of Texas at Austin (CEM-UT) studied linear motors for the U.S. Navy, to determine which types of linear motors show promise as weapon launchers. The many linear motors evaluated offer a wide variety of advantages or disadvantages. Synchronous motors require sliding contacts or flexible cables to bring power to the armature. These contacts or cables impose reliability limits on an accelerator design. Induction-type motors avoid this problem by electromagnetically inducing the armature current. However, they suffer from problems in efficiency and controllability.

One type of linear motor identified by the study was the reluctance motor. Its rotary counterpart is most frequently a stepper motor. It avoids the shortcomings of other synchronous motors by eliminating the armature windings. Since it has synchronous motor characteristics, it exhibits inherent controllability. Its primary drawback is the lack of technological background. In spite of their shortcomings, linear reluctance motors have advantages which make them good candidates as accelerators. Those advantages include inherent reliability and tolerance to hostile environments. These advantages seem to outweigh the difficulty of design inherent to a reluctance launcher.

Basic Operation

A reluctance accelerator consists of a series of solenoidal coils, each moving a ferromagnetic slug. Figure 1 shows the reluctance accelerator in its simplest form. Reluctance is the resistance to the creation of magnetic flux in the material surrounding the coil. Ferromagnetic material in the bore of the coil reduces this reluctance. Force is developed due to the change in reluctance of the material around the coil as the slug moves. The ferromagnetic slug has a greater magnetic permeability than the air it replaces. As a consequence, the flux can form more easily when the slug is centered on the coil. At this point, reluctance is minimum for a given flux level; it is also the position of least energy. When displaced from the centered position, magnetic forces will always act to restore the slug to its centered position. The linear reluctance motor is a series of coils activated sequentially to pull the slug along the bore. It is interesting to note that the slug is only pulled, never pushed. This is a disadvantage of the reluctance accelerator when compared with other synchronous accelerators which can push and pull by selectively choosing the relative polarity of the armature and stator windings.

![Figure 1. Simple reluctance accelerator](image.png)
applied to coil 2, as the slug approaches. At such time when the slug is near coil 2, the current in 2 reaches a desired maximum value. At this point, the voltage to the coil is switched off. The current which has been established in the coil is allowed to continue circulating through a reversed bias diode connected across the coil. Figure 3 is a simplified equivalent circuit which might be used to power each coil. Inductance in the circuit represents the coil inductance. Power sources are direct current but may not be a constant voltage. In a practical system, the switches will probably be solid state electronic. As a practical matter, the diode is necessary in any scheme in which a switch is used. It prevents a rapidly rising reverse voltage across the coil when the circuit is broken by the switch.

Figure 2. Half section through the reluctance accelerator

Figure 3. Simplified electrical circuit

After the switch to the coil is opened, current in the coil decays naturally, due to the resistance in the coil and diode.

At a time when the center of the slug approaches the center of the freewheeling coil, a negative voltage is applied across the coil if a significant current remains. Ideally, the current in the coil decreases to zero at the instant the slug and coil centerlines coincide. In this way, a retarding force is avoided. Alternatively a resistor, switched into the circuit, hastens the decay of the current.

**Force Calculations**

When current is flowing in the coil, magnetic energy is stored in the fields surrounding the coil. The flux is defined by the expression for magnetomotive force (MMF) is

\[ N_i = \Phi R \]  \hspace{1cm} (1)

where

\[ N_i = \text{MMF (amp turns) in the coil} \]
\[ \Phi = \text{total field} \]
\[ R = \text{reluctance of magnetic circuit around the coil} \]

In an air-core coil, reluctance is constant. Figure 4 shows this relationship. \( R \) is the slope of the curve.

Figure 4. Flux vs. MMF in an air-core coil

The stored magnetic energy is the shaded area on the curve and is defined as

\[ E_{\text{mag}} = \frac{1}{2} N_i \Phi \]  \hspace{1cm} (2)
\[ = \frac{1}{2} \Phi^2 R \]  \hspace{1cm} (air core) \hspace{1cm} (3)

**Approximate Closed Form Solutions**

The general equation for reluctance [1] is

\[ R = \frac{L}{\mu_r \mu_0 A} \]  \hspace{1cm} (4)

where
\[ l = \text{length of the magnetic path} \]
\[ \mu_r = \text{relative permeability} \]
\[ \mu_o = \text{permeability of space} \]
\[ A = \text{area crossed by magnetic flux} \]

In the reluctance motor described here, almost all of the reluctance appears in the gap between the stator and the armature slug. For this configuration, \( g \) becomes two times the width of the gap, \( g \), since the flux lines cross the gap twice in a circuit. When the armature slug is centered on a stator coil, the area, \( A \), becomes that of a cylindrical surface with diameter, \( d \) and with a length of \( 1/2 \) of the slug length. If the slug length is \( p \) and it's diameter is \( d \), then equation 4 becomes

\[ R_e = \frac{4g}{\mu_o \pi dp} \]  

since

\[ g = \text{gap} \]
\[ d = \text{bore diameter} \]
\[ p = \text{slug length} \]
\[ \mu_o = \text{permeability of space} \]
\[ \mu_r = 1 \text{ for air} \]

The effective length of a coil is about two times the pole pitch. For the linear case, equation 3 can be differentiated with respect to movement along the axis of the motor, \( x \), to obtain the force generated by the motor.

\[ F = -\frac{dE}{dx} = -\frac{1}{2} \Phi^2 \frac{dR}{dx} \]
\[ \Phi = \text{const} \]
\[ = (N_i)^2 \frac{4g}{\mu_o \pi dp^2} \]  

This relationship has been described previously for the case of a rotary reluctance motor by Slemon and Straughen. [3]

As a practical matter, this equation gives very inaccurate results. One inaccuracy is caused by flux leakage. This occurs when some of the flux lines do not pass through the slug. Another inaccuracy is caused by applying linear analysis to a nonlinear problem. The net result is that classical closed form expressions for reluctance accelerator force may be in error by as much as an order of magnitude. To arrive at a design for a reluctance accelerator, the designer must resort to nonlinear finite element techniques.

**Nonlinear Analysis**

In reluctance accelerators with ferromagnetic material, reluctance is not constant because of the tendency of that material to saturate. Figure 5 shows the saturation curve. \( R_e \) is large for low MMF, but decreases as \( N_i \) increases. This curve is usually defined in terms of \( B \), flux density, instead of \( \Phi \). The stored magnetic energy is still defined by equation (2). However, since \( R_e \) is no longer constant equation (3) no longer applies. It is fair to say, however, that stored magnetic energy is a function of flux and reluctance

\[ E_m = f(\Phi, R_e) \]  

Figure 5. Flux vs. MMF for ferromagnetic material

Fortunately for the reluctance accelerator designer, flux reluctance and stored magnetic energy are state properties of the system and are not time dependent. They depend only on the geometry of the accelerator at a particular point in time and of the distribution of the current in the coil. As a result, FEA computer codes such as TEXMAP developed at CEM-UT define stored energy, flux, and reluctance as a function of slug position and current density in the coil or coils. [2] Figure 6 shows a typical set of curves for a reluctance accelerator such as the one shown in figure 2. This curve shows that reluctance is lowest when the slug is centered on the coil or at top dead center (TDC) using engine terminology. A plot of stored magnetic energy vs. position and flux has the same general shape. The energy defined by such a curve is the source of the centering force on the slug. For the system in which energy is being neither added nor removed the change in kinetic energy of the slug equals change in stored magnetic energy:

\[ F = \frac{d}{dx} (E_m) |_{\Phi=\text{const}} \]

This implies that the force on the slug is proportional to the slope of the curve in figure 6. A typical plot of the force on the slug is shown in figure 7.

Figure 6. Reluctance vs. slug position
Finite element code analysis of typical accelerator geometries has shown that this point of maximum force occurs when the slug is located approximately as shown in figure 8 or about one-pole pitch removed from TDC center. For a small time interval $\Delta t$, the energy equation for reluctance accelerator is,

$$V_i \Delta t = \Delta E_m + \Delta W + I^2 R \Delta t$$  \hspace{1cm} (10)$$

where

- $V_i \Delta t$ = energy added to system from power supply
- $\Delta E_m$ = change in stored magnetic energy
- $\Delta W$ = work
- $I^2 R \Delta t$ = heating caused by resistive losses

Losses due to eddy currents and hysteresis can also be added to the equations, but if laminated high performance ferromagnetic materials are used, these secondary losses are small in comparison to the other terms.

TDC. At that location, reluctance is very near its minimum value and the reluctance curve is relatively flat. Since $d\Phi/dx$ is near zero, little force is developed by the accelerator. The power applied at this point goes mostly into stored magnetic energy and resistive losses. At a point near the maximum force position, power is removed and the coil freewheels. During the freewheel period, stored magnetic energy is converted to slug kinetic energy and heat. In a lossless system, the change in kinetic energy while moving from position 1 to 2:

$$\Delta W = f(\Phi, R_1) - f(\Phi, R_2)$$  \hspace{1cm} (11)$$

where

$$f(\Phi, R) = \text{nonlinear function describing the stored magnetic energy as a function of flux and reluctance}$$

Since no voltage is applied to the coil during the freewheel period, total flux remains constant. Transfer of energy is caused by change in reluctance alone. Since the stored energy at a given flux is roughly proportional to reluctance, a figure of merit for an accelerator coil can be defined,

$$\eta = \frac{R_1 - R_2}{R_1} \bigg|_{\Phi=\text{const.}}$$  \hspace{1cm} (12)$$

This figure of merit is approximately equal to the fraction of the stored magnetic energy which can be converted to mechanical energy. In a lossless system, this figure of merit would be the acclerorency of the accelerator. This figure of merit is a very convenient way to evaluate the "goodness" of a mechanical design. Using the FEA code, the designer evaluates reluctance of the slug-coil configuration with the slug centered and for a flux level near saturation. The designer then finds the reluctance with the slug displaced by two-pole pitch lengths and at the same flux. The figure of merit is then found from equation (12). As a practical matter, flux is a dependent variable in the FEA code. The independent variable is MMF (ampere turns). For this reason, a trial and error method must be used to get reluctance at the two points and for the same flux. In spite of this problem, this method of determining merit is much easier than generating a complete reluctance, current, position matrix with a FEA mesh for each position.

In conceptual design studies at CEM-UT, mechanical designs were found with figures of merit of 0.75 or more. This means that in the absence of resistive losses, reluctance accelerators can be made relatively efficient.

### Resistive Losses and Wire Size

Electric motors, in general, and linear electric motors, in particular, can be made very efficient. However, when used as an accelerator, high efficiency is much harder to achieve. The reason is that energy losses in a coil are proportional to the time during which current is flowing. Flow time is inversely proportional to speed. This would imply that the heat loss in the first coil of a 30-coil accelerator is roughly 10 times that of the 30th coil. Average loss of the accelerator is about twice that of the last coil. The cross sectional area of the reluctance launcher coil must be large enough to prevent resistive
losses from raising the temperature and the coil beyond the limits of the wire insulation. Even larger cross sections minimize resistive losses. However, larger wire cross sections reduce the pole area. A smaller pole area increases reluctance, thus reducing the figure of merit. A trade-off must be made to insure that the optimum wire size is used to achieve the desired performance.

**Power Supply Considerations**

Power supply waveshapes, which are more complex than those from simple switching schemes can be used for a reluctance accelerator. However, in order for the accelerator to work well, the current in the coil must be brought to near zero as the TDC position. In practice, this is hard to achieve with an open-loop supply and even more difficult with polyphase supplies. Closed-loop controls, which sense position and velocity, are necessary to control switching of voltage to the coils.

**Conclusion**

Reluctance accelerators offer an interesting choice of driver for applications in which the environment is hostile. Although these devices are relatively difficult to design, analytical tools are available to complete a successful design.

**Acknowledgments**

This research is supported by Naval Sea Systems Command, David Taylor Research Center, and Applied Research Laboratory under contract no. N00039-88-C-0043.

**References**

