Parametric Design of Linear Reluctance Actuators.

R.E. Clark, University of Sheffield.

Linear reluctance actuators have a number of advantages over permanent magnet actuators, in terms of simple rugged construction and capability to operate in harsh environments and at elevated temperatures. The vast majority of, reluctance actuators have a variable-airgap and exploit the normal component of force between an iron armature and the stator, such as pot core solenoids, which are widely used in applications requiring a high specific force capability. However, since the force for a given excitation current diminishes rapidly as the airgap length increases, (approximately with the square of airgap) they are generally only suitable for short stroke applications (typically in the sub-millimetre range). Further, the rapid increase in force that occurs as the armature approaches the stator means the actuator is difficult to control. For applications that require longer strokes and/or improved controllability, it is necessary to resort to actuator topologies that exploit the tangential component of force, despite the fact that they have considerably lower specific force capability.

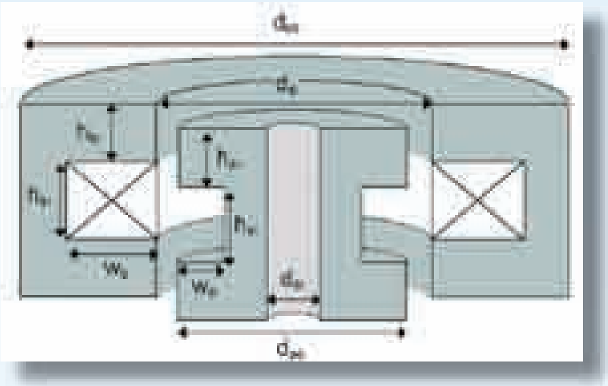

Figure 1 : Cross-section through a cylindrical linear reluctance actuator.

Tangential force actuator

One actuator topology that is well suited to medium-stroke applications is shown schematically in figure 1. It has a cylindrical geometry, although the same basic configuration can also be realised in a rectangular geometry. It consists of a ferromagnetic armature and stator, which carries the excitation coil. When the coil is excited, the stator and armature teeth will tend to align in order to minimise the magnetic circuit reluctance, thereby producing an axial force. Potential application areas for this type of actuator include direct drive spool valves and variable geometry turbochargers. The dimensions of such a tangential force actuator, which has been designed to achieve a rated force of approx 60 N with a stroke of 8 mm, are given in table 1.

d_{so}	100 mm	d_{ao}	64.5 mm
d_{si}	65.5 mm	d_{ai}	20 mm
h_{s1}	12 mm	h_{a1}	12 mm
h_{s2}	9 mm	h_{a2}	9 mm
w_s	13.25 mm	w_a	6.75 mm

Table 1 : Dimensions for the case-study actuator.

FLUX2D Analysis

Although the actuator can be designed using analytical magnetic circuit techniques, improved accuracy is obtained by using finite element analysis, as it can directly account for all the salient features, such as localised saturation and flux-leakage. An axisymmetric model of the actuator has been developed using FLUX2D. The problem region and a typical mesh, with 5367 elements, and 11304 nodes, is shown in figure 2. The armature is defined within a mobile co-ordinate system to allow the movement to be readily modelled. The stator and armature are both manufactured from EN1A mild steel and are modelled using the BH characteristic measured on a toroidal test sample. The stator magnetic circuit is split, as shown in figure 2, to allow the insertion of a pre-wound coil. The small parasitic air gap that is created due to the imperfect contact surfaces is accounted for with a linear air-gap region (thickness = 0.1mm) without the need for an extremely fine discretised mesh in this region.

Typical field plots and the force displacement characteristic for this actuator with an excitation mmf of 800 A.turns, are shown in figure 3 which shows that for a given current, there is a significant roll-off in axial force as the armature and stator teeth come into alignment. No net force is produced when the poles are fully aligned (although it is very stiff with respect to any axial displacement from

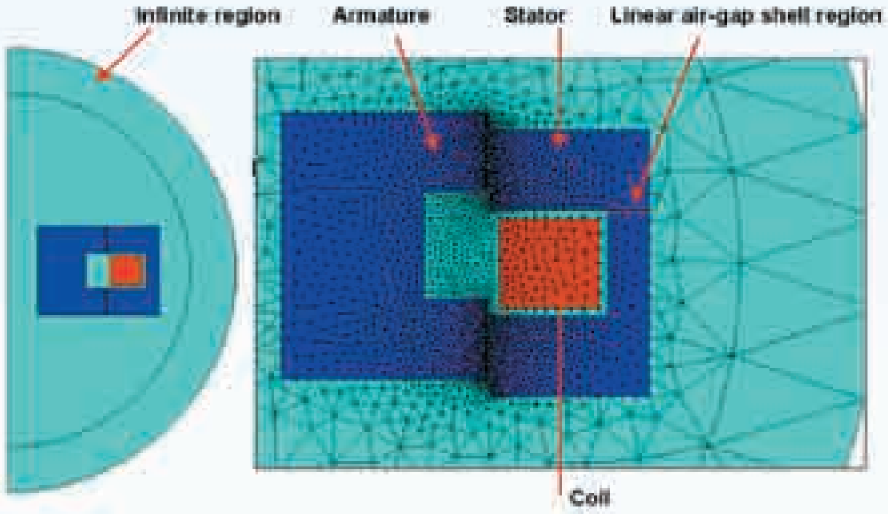

Figure 2: Force-displacement characteristic for a linear relucatnce, tangential-force actuator.

(continued on page 20)

Parametric Design of Linear Reluctance Actuators. (continued)

R.E. Clark, University of Sheffield.

this position). However, many applications require an essentially constant force for a given current over a specified working stroke, in order to simplify the control and reduce system complexity, e.g. to use current control to precisely control position against a linear spring load without the need for position feedback. In an actuator of the type shown in figure 1 such a characteristic could only be realised by restricting the working stroke to a limited proportion of the maximum stroke, typically some 50-60%. Such a poor utilisation of the actuator results in a reduced stroke relative to the overall length, which may be unacceptable when space is at a premium.

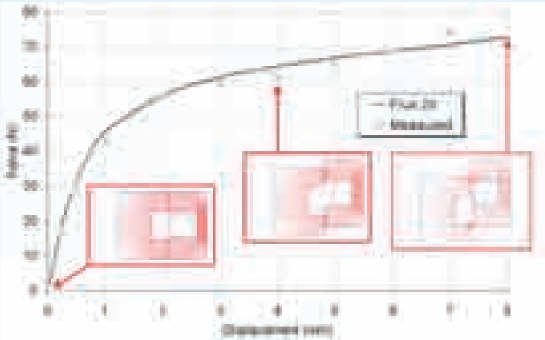

Figure 3: Force-displacement characteristic for a linear reluctance, tangential-force actuator

Force compensation rings

A convenient method of enhancing the force capability as the armature approaches the fully aligned position, without unduly adding to the overall length, is to add a profiled compensation ring at one end of the stator pole as shown in figure 4, which in practice is manufactured as an integral part of the upper stator pole. The compensation ring introduces a normal component of axial force that supplements the tangential component of axial force as the armature and stator poles come into alignment. Figure 4 shows a typical field plot in the region of the compensating ring with the armature and stator teeth aligned.

Parametric Study

The dimensions of the compensating ring, are shown in figure 5. Providing the dimensions γ and δ are selected to prevent saturation, the leading dimensions which govern the effect of the compensating ring are α and β. The radial length, α, determines the overlap area and therefore the magnitude of the normal force component for a given separation between the compensating ring and the top face of the armature, while β effectively determines the phase of the normal force-displacement characteristic with respect to the stroke of the actuator. However, since the two force components cannot be independently controlled, the net force-displacement characteristic for a given current can only be tailored at the design stage. The influence of these parameters has been investigated using the in-built parametric modelling capability of FLUX2D, which has the significant advantage of allowing the force-displacement characteristics for a range of designs to be generated automatically.

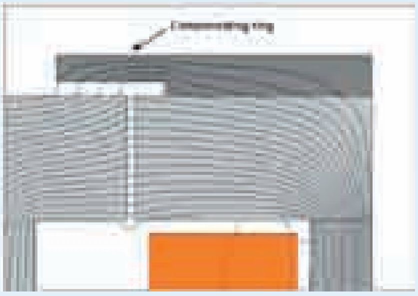

Figure 4: Typical field plot with compensating ring

For example, figure 6 shows the magnitude of the axial force in the fully aligned position as both α and β are varied, with an excitation mmf of 800 A.turns. This shows that a number of combinations allow the specified force of 60N in the aligned (zero displacement) position to be achieved. However, achieving this value of force at the end of the stroke does not guarantee a constant force-displacement characteristic and the full characteristic for candidate designs which achieve the specified force at zero displacement are then investigated using a further parametric study.

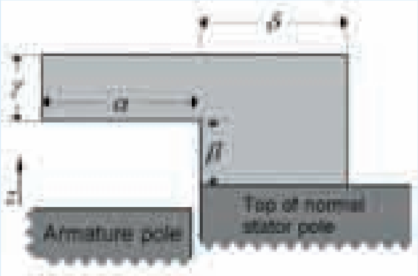

Figure 5: Leading dimensions of compensating ring

Tailoring Force Characteristics

Figure 7 shows the predicted force-displacement characteristics for two combinations of α and β which both produce 60 N at 0 mm, which demonstrates that a near linear characteristic can be obtained, while another combination still exhibits a significant non-linearity over the stroke due to inappropriate phasing of the force components.

Figure 6 also shows that some combinations of α and β result in high forces at the end of the stroke, which may exceed the rated force capability of the actuator. By way of example, figure 8 shows the force-displacement characteristic when α=2.25 mm and β =0.5 mm.

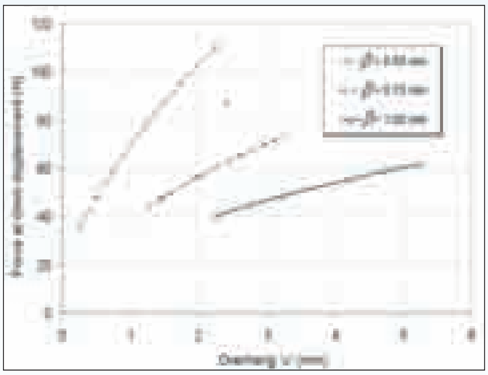

Figure 6: Variation of axial force in the aligned position with dimensions of the compensating ring

(continued on page 20)

Parametric Design of Linear Reluctance Actuators. (continued)

R.E. Clark, University of Sheffield.

Although the force-displacement characteristic is highly non-linear over the last 1mm of the stroke it is useful for many applications. For example, an actuator for a fluid control valve may be required to have a reasonably constant force over the majority of the stroke to allow precise control of the fluid flow, and also have the capability to hold the valve in a closed position. Although dependant on the operating duty cycle, such a force-displacement characteristic may allow the average current to be reduced, thereby improving the efficiency.

Experimental Validation

The measured results presented throughout this article were obtained using a custom test-rig. The force on the armature is measured using a Pioden UF2 225N load-cell by means of a precision shaft supported on 3 linear bearings. The armature position was measured by a Heidenhein MT25 optical encoder having a resolution of 0.5 μm. Good agreement between the force-displacement characteristics and measured results are shown in the figures.

Conclusion

There is considerable scope to tailor the force displacement characteristic of a linear reluctance, tangential-force, actuator with the use of a compensating ring. However, due to the complex interaction of the tangential and normal components of force the net force displacement characteristic must be considered at the design stage. The parametric capability of FLUX2D allows a number of design to be rapidly investigated, while fully accounting directly for salient features such as saturation, leakage and manufacturing features.

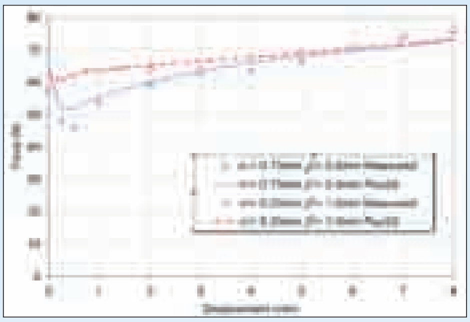

Figure 7: Measured and predicted force-displacement characteristics for two designs that achieve 60N in the aligned position.

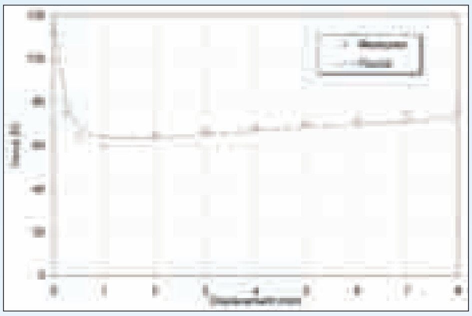

Figure 8: Measured and predicted force-displacement characteristics for a high holding force design.

LDIA 2003. *4th International Symposium on Linear Drives for Industry Applications - IEE Midlands Engineering Centre, Austin Court, Birmingham, 8 - 10 September 2003.*

LDIA 2003, co-sponsored by the IEE and IEEJ, continues the series of symposia (Nagasaki - 1995, Tokyo - 1998, Nagano - 2001) which brings together engineers and scientists from different backgrounds to review progress and exchange ideas on the design control and application of linear machines and drives. Topics covered include:

Electromagnetic linear motors and actuators
- linear induction / synchronous / reluctance motors,
- linear permanent magnet motors,
- linear electromagnetic actuators ,
- surface motors / spherical actuators.

Other linear motion systems
- ultrasonic / electrostatic linear motors,
- pneumatic / hydraulic systems.

Design, analysis and dynamic simulation
- analytical / numerical modelling,
- electromagnetic field analysis,
- coupled problems / system simulation.

Control systems
- single / multi-axis control,
- sensorless control / optimal control.

Magnetic levitation
- electromagnetic / electrodynamic levitation,
- combined levitation / propulsion,
- HT superconducting magnetic levitation.

Applications
- automotive / aerospace/ industrial,
- transportation /conveyance,
- factory automation,
- medical /consumer products.

Further information on LDIA 2003 can be obtained via ***www.sheffield.ac.uk/ldia2003*** or from the symposium secretariat at the University of Sheffield, Tel/Fax: +44 2225195/6, Email: ldia03@sheffield.ac.uk.