Tailoring Force-Displacement Characteristics in Medium-Stroke Linear Variable Reluctance Actuators

Richard E. Clark, Geraint W. Jewell, Paul Stewart, and David Howe

***Abstract*—The paper is concerned with the design of medium-stroke variable reluctance actuators that exploit the tangential component of force. A method of compensating for the roll-off in force as the stator and armature come into full alignment is presented, and the scope which this offers to tailor the force-displacement characteristic to meet the demands of a particular application is illustrated by means of a case study. The case study includes finite element analysis and experimental measurements on an actuator having a stroke of 8 mm and a rated force capability of 60 N.**

***Index Terms*—Actuators, magnetic analysis, magnetic forces, reluctance machines.**

I. INTRODUCTION

LINEAR, variable-airgap, reluctance actuators that exploit the normal component of force between an iron armature and the stator, such as pot core solenoids, are widely used in applications that require a high specific force capability. However, since the force for a given excitation current diminishes rapidly as the airgap length increases, they are generally only suitable for short stroke applications (typically in the millimeter and submillimeter range). Further, the rapid increase in force that occurs as the armature approaches the stator makes such actuators difficult to control, particularly in terms of controlling the impact velocity during dynamic operation. 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.

One such actuator topology that is well suited to medium-stroke applications is shown schematically in Fig. 1. It has a cylindrical geometry, although the same basic configuration can also be realized in a rectangular geometry. In order to minimize the copper loss, such an actuator requires a relatively small radial airgap (usually of the order of a few tenths of a mm). In the particular actuator shown in Fig. 1, the stator and armature teeth have the same width (i.e., $h_{a2} = h_{s2}$). Hence, it produces no net axial force when the teeth are fully aligned (although it is likely to be very stiff with respect to any axial displacement from this position). Even if the stator teeth are wider than the armature

Manuscript received February 14, 2002; revised May 22, 2002. This work was supported by The Royal Academy of Engineering, The Framework V Programme of the European Union and the U.K. Engineering and Physical Sciences Research Council.

The authors are with the Department of Electronic and Electrical Engineering, The University of Sheffield, Sheffield S1 3JD, U.K. (e-mail: r.clark@sheffield.ac.uk).

Digital Object Identifier 10.1109/TMAG.2002.802131.

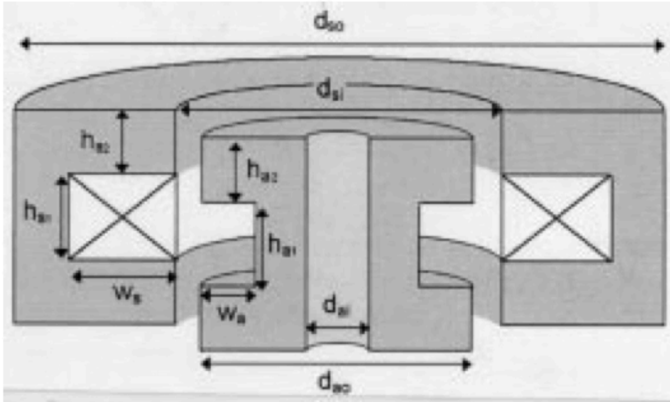

Fig. 1 Cross section though a cylindrical linear reluctance actuator.

teeth, the axial force drops very significantly when they overlap fully.

As a consequence, for a given current, there is a significant roll-off in axial force as the armature and stator teeth come into alignment. 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. By way of example, in a system in which the mechanical load is dominated by a linear spring, the armature position can be controlled with a reasonable degree of precision, simply by controlling the current, thereby eliminating the need for position sensors. However, in an actuator of the type shown in Fig. 1, such a characteristic could only be realized by restricting the working stroke to a limited proportion of the maximum stroke, typically some 50%–60%, although, clearly, this is dependent on the dimensions of the particular actuator design. Such a poor utilization of the actuator results in a reduced stroke relative to the overall length, which may be unacceptable when space is at a premium.

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 Fig. 2. In practice this feature could be 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 approach full alignment. 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 geometry of the compensation ring can be defined in terms of four dimensions, *viz.* α, β, γ and δ as defined in Fig. 2.

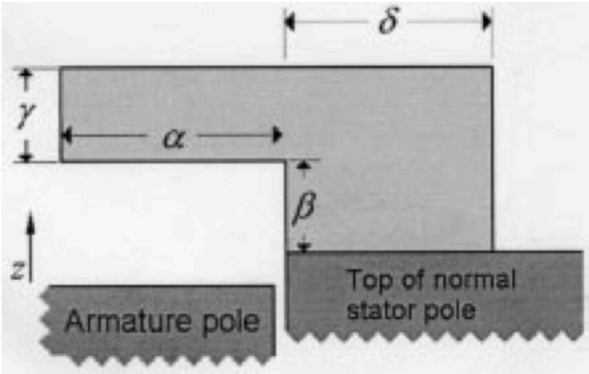

Fig. 2. Leading dimensions of compensating ring.

TABLE I
ACTUATOR DIMENSIONS

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

Provided that the dimensions γ and δ are selected such that they do not give rise to undue saturation at the rated current, they will not exert a significant influence on the net force-displacement characteristic.

The dimension α in Fig. 2 determines 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. In order to illustrate the scope that these two parameters offer for tailoring the force-displacement characteristic to the needs of a particular application, a case study, encompassing both finite element analysis and experimental measurements, was undertaken on the actuator whose dimensions are shown in Table I, and whose coil has 220 turns of 0.63-mm diameter wire.

II. Finite Element Analysis

Force-displacement characteristics were calculated for the actuator in its basic form and with the addition of a series of compensation rings using two-dimensional (axi-symmetric) magneto-static finite element analysis (MEGA package), a typical mesh comprising 14 000 first-order elements. The iron circuit of the actuator was modeled using a published magnetization curve for EN1A mild steel [1]. The calculated force-displacement characteristic for the basic actuator, with an excitation mmf of 800 A.turns is shown in Fig. 3 (0 mm corresponding to the stator and the armature poles being fully aligned). A practical target in terms of producing a near constant axial force over the stroke of 8 mm, is 60 N at zero displacement with a coil mmf of 800 A.turns. Fig. 4 shows the finite element calculated axial force at zero displacement as a function of α for three different values of β, *viz.*, 0.5 , 0.75 , and 1 mm (in each case with $\gamma = 2$ mm and $\delta = 17.25$ mm).

As will be seen, there are a number of combinations of α and β which give rise to the desired axial force of 60 N at zero

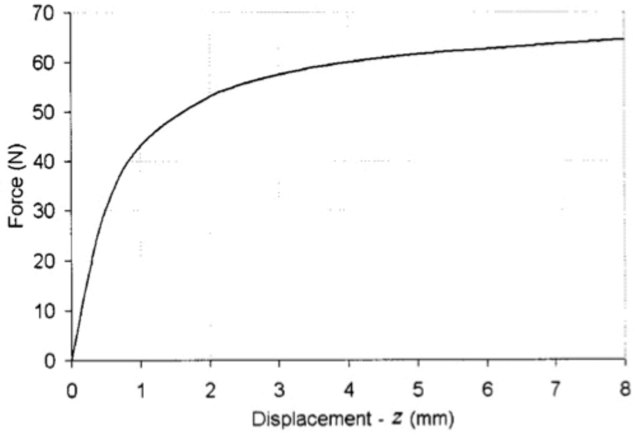

Fig. 3. Finite element predicted force-displacement characteristic of the basic actuator with 800 A.turns excitation.

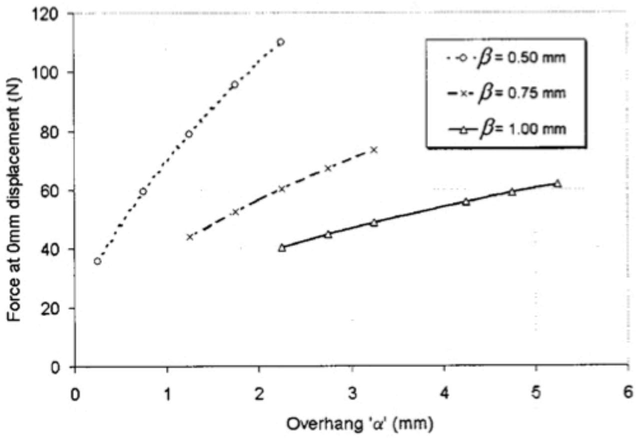

Fig. 4. Variation of axial force at the zero displacement as a function of α and β with an mmf of 800 A.turns.

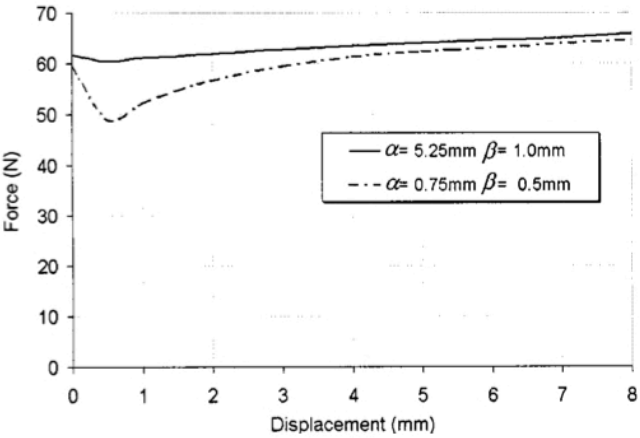

Fig. 5. Finite element predicted force-displacement characteristics for two designs which meet the 60 N force at zero displacement specification.

displacement. However, achieving this value of force at the end of the stroke does not, in itself, guarantee an essentially constant force-displacement characteristic. This is illustrated in Fig. 5 which shows the predicted force-displacement characteristics for two combinations of α and β which both produce 60 N at 0 mm. As will be seen, with $\alpha = 5.25$ mm and $\beta = 1$ mm, an almost constant force is achieved, whereas with

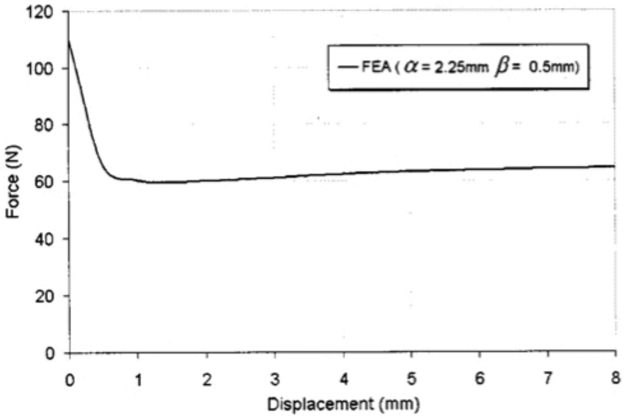

Fig. 6. Finite element predicted force characteristics with $\alpha = 2.25$ mm and $\beta = 0.5$ mm.

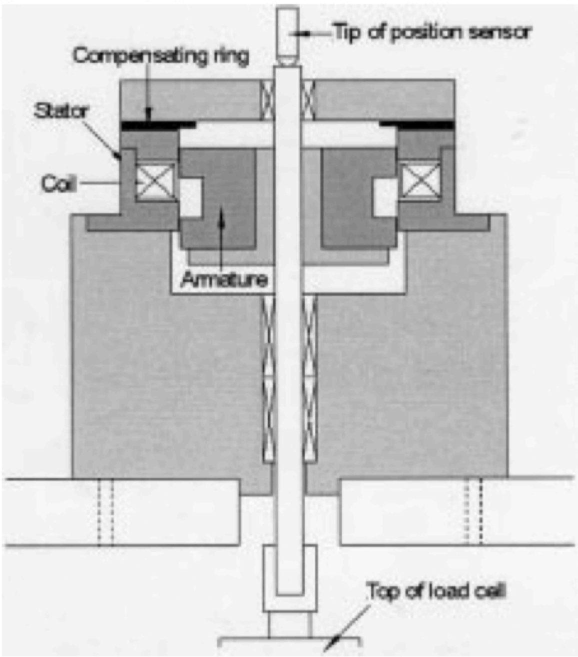

Fig. 7. Cross-sectional drawing of test-rig.

$\alpha = 0.75$ mm and $\beta = 0.5$ mm there is a considerable reduction in the axial force at a displacement of ~0.5 mm. This highlights the fact that the distance β controls the relative phasing of the normal force-displacement characteristic relative to the tangential force-displacement characteristic. An interesting feature of Fig. 4 is that some combinations of α and β result in large forces at the end of the stroke, which may exceed the rated force capability of the actuator. By way of example, Fig. 6 shows the finite element predicted force-displacement characteristic when $\alpha = 2.25$ mm and $\beta = 0.5$ mm. Although the force-displacement characteristic of Fig. 6 is highly nonlinear over the last 1 mm of the stroke, it may nevertheless be a good fit to certain applications. For example, an actuator for use in a fluid control valve may be required to have a reasonably constant force over the majority of the stroke in order to facilitate precise control of the fluid flow, and also have the capability to hold the valve in a closed position. Dependant on the operating duty cycle, such a force-displacement characteristic may allow the average current to be reduced, thereby improving the efficiency.

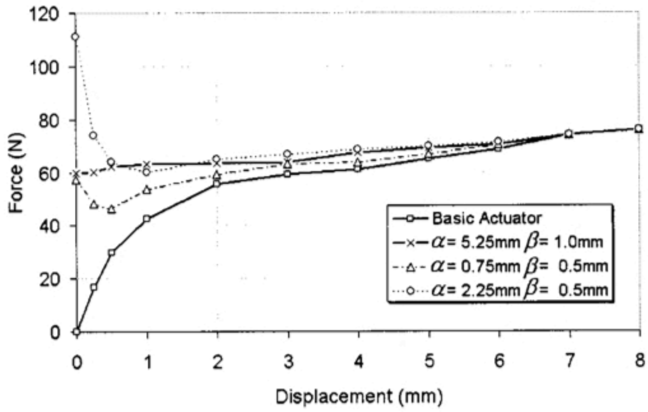

Fig. 8. Measured force-displacement characteristics.

III. Experimental Validation

In order to validate the findings of the finite element analysis, the test-rig of Fig. 7 was constructed (the compensating ring with $\alpha = 5.25$ mm and $\beta = 1$ mm being shaded in black to aid clarity). To measure the force, the armature is connected to a Pioden UF2 225N load-cell by means of a precision shaft supported on three linear bearings incorporated within a large Aluminum housing and top-plate. The armature position was measured by a Heidenhein MT25 optical encoder having a resolution of 0.5 μm. Fig. 8 shows the measured force-displacement characteristics for the original actuator and with the addition of compensating rings having the dimensions assumed in the finite element analysis. As will be evident, the measurements agree well with predictions.

IV. Conclusion

The paper has illustrated that there is considerable scope to tailor the force-displacement characteristics of linear variable-reluctance actuator to suit the needs of different applications by adding relatively small compensating rings.

References

[1] K. Harmer, G. W. Jewell, and D. Howe, "Experimental validation of a finite element based dynamic simulation technique for fast-acting, short-stroke, linear actuators," in *Proc. LDIA98*, Tokyo, Japan, Apr. 1998, pp. 220–223.