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Design and investigation of high-speed, large-force and long-lifetime electromagnetic actuators by finite element modelling

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Abstract: Electromagnetic (EM) solenoid actuators are widely used in many applications such as the automobile, aerospace, printing and food industries where repetitive, often high-speed linear or rotating motions are required. In some of these applications they are used as high-speed 'switching' valves for switching pneumatic channels. This paper describes the finite element (FE) modelling and design of high-speed solenoid actuators. Operating at frequencies between 150-300 Hz, these actuators are unique in terms of the large force they produce (8-15 N) and the requirement for very long lifetime (2-5 billion cycles). The complex nature of electromagnetic, motional and thermal problems is discussed. The methodologies for FE modelling of such high-performance actuators are developed and discussed. These are used for modelling, design, performance evaluation and prediction of the above high-speed actuators. Modelling results showing some of the key design features of the actuators are presented in terms of force produced as a function of various design parameters.

1. Introduction

Electromagnetic (EM) solenoid actuators of wide variety of sizes, shapes, power outputs and technological realizations are used in many applications where discrete cyclic motions are required. Compared to other actuating mechanisms based on, for example, piezoelectric and hydraulic principles EM actuators are simpler, cheaper, repairable, robust, and easier to manufacture. Although the analysis and design of such actuators are well covered in the literature [1-3], there are, however, very few situations which involve commercial EM actuators that normally operate under continuous duty cycles at frequencies between 150-300 Hz, producing a relatively large force (8-10 N). Combined with a stroke length of 0.05-0.1 mm, 'on' and 'off' times of 0.2 ms and 0.46 ms, and a requirement for multibillion cycle operation (in excess of 5 billion cycles) without maintenance, these actuators operate at the limit of what can be achieved by solenoid-based EM actuator technology.

This paper investigates one of the designs of actuators of this type, used as pneumatic ejector valves in high-speed optical food sorting machines [4]. The whole area of systematic research into high frequency EM valve-based ejector technology is new. To our knowledge, apart from previous 'trial and error' methods used in industry, no comprehensive research has been done so far in this area. Given the demanding fast duty cycle, high frequency of operation, high reliability and robustness needed for the ejector technology, the EM ejector valve being developed should be unique, meeting very tight design and rigorous performance specifications. Some of the novel aspects of the design being pursued include the minimisation of the overall size of the valve, and meeting the constraints of the particular geometric and material parameters of the magnetic circuit and the dedicated control circuitry used.

2. Modelling of High-Speed Actuators

Figure 1 shows the simplified schematic of one of the designs of a high-speed solenoid actuator used as ejector valves mentioned above. It is essentially an on/off valve actuator whose active components comprise an excitation coil wound around a magnetic core that attracts or releases a movable valve plate depending on the excitation state of the coil. Very tight design and rigorous performance specifications make these ejectors used in high-speed sorting applications unique in terms of their design, manufacture and reliable exploitation. Typically, an individual ejector fits into an array of 32, 64, 96 or 128 ejectors and to maintain the maximum packing density they are often packaged in serviceable modules of two, four or more ejectors. All these factors put severe constraints on a number of the geometric dimensions (e.g. TCL, TV shown in figure 1) of individual ejectors, some of which are directly linked to their overall lifetime and the 'resolution' of the optical sorting to be carried out.

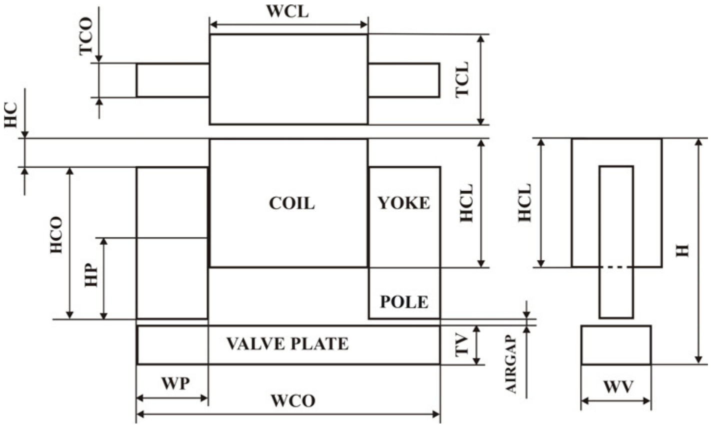

Figure 1. Simplified schematic showing the main constructive features of a high-speed EM actuator used as an ejector valve in an optical sorting machine.

EM actuators rarely operate in the steady state and various operational factors like start-stop duty, operating frequency, response time and damping have a significant influence on their design. The EM part of the system is represented by electric and magnetic circuits with self-inductance, resistance and reluctance which are subject to variations, in general, due to eddy currents, saturation conditions, motional electromotive force (e.m.f.), demagnetisation and hysteresis. The mechanical part is represented by friction, damping, elasticity and inertia as well as external forces. Together these two parts form an equivalent electromechanical system which has to be optimised against the performance requirements and the complex behaviour of which is subject to static and dynamic analyses of these actuators. For high frequency EM ejectors, the thermal problem of temperature distribution and heat dissipation is of vital importance. Like all other electrical devices, they generate losses (e.g. ohmic loss in the winding, core and any circulating-current losses, etc.) manifested in the form of heat and temperature rise which may be considered to be one of the dominant factors in limiting the life of most high-speed actuators. Temperature-rise may significantly increase the winding resistance, impairing control. The frequency response may be altered because both the electrical and the mechanical time constants are temperature sensitive. Often, when tightly packed, ejectors may create serious problems of heat sinking from individual units. Also the diverse combination of materials used and the very extensive duty cycles may give rise to a myriad of thermal problems, unique only to high-speed actuators. The solutions to these problems will have a direct impact on the cost, size, reliability and feasibility of a given design. Compared to conventional solenoid actuators, the nonlinear and transient

EM, thermal, and motional problems being solved in the above ejector valves pose substantial challenges because of their high frequency of operation and the requirement for a continuous and fail-safe duty cycle.

In general, the mathematical model of the above electromechanical system can be adequately represented by the following four differential equations given below. In summary these represent (1) an electrical circuit equation for the excitation coil and control circuitry, (2) a nonlinear magnetic field equation (Poisson's equation) for the flux, the change of which changes the EM energy storage in the system and produces the magnetic force, (3) a mechanical equation for this force, load (e.g. pneumatic force), friction, inertia, acceleration, speed and displacement, and (4) a nonlinear thermal diffusion equation for the conduction of heat produced by electrical power losses.

$$u(t) = iR + N\frac{d\Psi(i,z)}{dt} \tag{1}$$

$$\mathrm{curl}(\nu\,\mathrm{curl}\,\boldsymbol{A}) = \boldsymbol{J} - \sigma\frac{\partial \boldsymbol{A}}{\partial t} + \sigma\boldsymbol{V}\times(\mathrm{curl}\,\boldsymbol{A}) \tag{2}$$

$$F_m(i,z) = m\frac{d^2z}{dt^2} + B\frac{dz}{dt} + Kz + F_e \tag{3}$$

$$\rho C\frac{\partial T}{\partial t} - \nabla\cdot\left[k(T)\nabla T\right] = q^B \tag{4}$$

In the above equations $u(t)$, i and $\Psi(i, z)$, and z are the applied voltage, coil current, flux linkage with the coil, and the displacement of the valve plate respectively, R and N are the coil resistance and the number of turns in the coil, $\boldsymbol{J}$, $\boldsymbol{A}$, $\boldsymbol{V}$ are the coil current density, magnetic vector potential, and the plunger (valve plate) velocity; m, B, K, F_m and F_e are the mass of the valve plate, viscous damping coefficient, spring constant, magnetic force and the load force respectively; and T, and q^B are the temperature and the internal rate of heat generated per unit volume respectively. The material parameters ν, σ, ρ, C and k denote the magnetic reluctivity ($\nu = 1/\mu$, μ is the permeability), the electric conductivity, density, specific heat and the thermal conductivity respectively. In general, these equations are nonlinear and inseparable. The current produced by equation (1) creates the magnetic field given by equation (2) and produces the magnetic force which causes the displacement, speed and acceleration of the actuator obtained from equation (3). The current also generates the heat (per unit volume) and the resulting temperature distribution given by equation (4). There are two main approaches to the coupled solution of these equations: the direct coupled approach and the indirect coupled approach, neither of which alone is suitable to incorporate the whole array of factors which are expected to be encountered in the practical exploitation of high-speed ejector valves. These assume the necessity for qualitative and quantitative assessments of those factors that introduce nonlinearities in the system, in order to justify the use of one (or several) of these methods for modelling and simulation purposes. For example, if the motional and eddy-current effects are negligible, the winding inductance can be taken as constant and the decoupling of the equations would be adequate for dynamic analysis. On the other hand, the direct coupled approach would be more appropriate if the eddy-current effects are negligible, but saturation and motional nonlinearities are prominent. Thus a methodology which includes the provision for using both coupled or/and decoupled solutions of electromechanical equations by *a priori* qualitative and quantitative justification would be most appropriate. The methodologies for modelling and design of EM ejector valves are based upon the modelling and computation of the 2D/3D nonlinear magnetic field distribution using the numerical finite element (FE) technique. This involves the steady-state and transient solutions of the nonlinear Poisson's equation for which there are no analytical solutions. The results are used for design optimisation and for investigating the effects of various geometric, material, EM and mechanical parameters on the output performance of ejectors. The thermal modelling involves the development of

2D/3D thermal models and the FE solution of the steady-state and/or transient heat transfer equations given by equation (4) above. The heat sources needed for this are given by the various losses mentioned above. The coupling of the magnetic field and the thermal equations (owing to the dependence of the power density on the magnetic vector potential and the temperature dependence of the magnetic permeability and electric conductivity) may be realised either by indirect coupling (in which the equations are solved separately and coupled by means of power density and an iterative process is used to compute the power density and the temperature distribution) or by direct coupling in which the equations are solved simultaneously. The prime aim here is to obtain a vital insight into the thermal behaviour of the ejector valves and to enable quantification of the effects of various factors that affect such behaviour. The FE models also enable the simulation of possible modes of thermal failure and create an essential basis for the design of a predictable, thermally stable and reliable actuator sub-system.

3. Results of Analysis and Discussion

3.1. Effects of material and geometric parameters

In the design of an EM actuator of the aforementioned performance requirements, the material and geometric parameters play a very important role. The need for delivering a relatively large force and a very fast response time under multibillion cycle operational regimes at 300 Hz puts an added importance on some of the crucial design parameters. Some of the effects, which would otherwise play a minor role in the design of low-frequency actuators operating under duty cycles far below that is required of the actuator discussed here, are likely to be magnified under multibillion cycle operations.

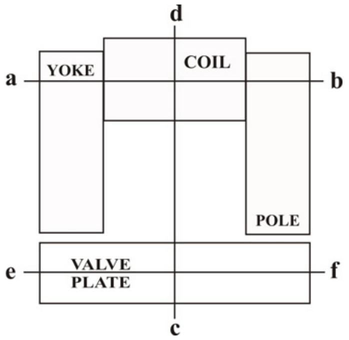

Figure 2. Schematic of the EM actuator given in figure 1 showing the lines ab, cd and ef along which magnetic flux densities are calculated in figures 3, 4, and 5. (not drawn to scale)

One of the crucial issues here is the mechanical wear of the moving part of the actuator i.e. the valve plate. It has been established by extensive testing of the ejector valves mentioned above that the mechanical wear of the valve plate is the weakest ‘link’ that contributes to the failure mode of these

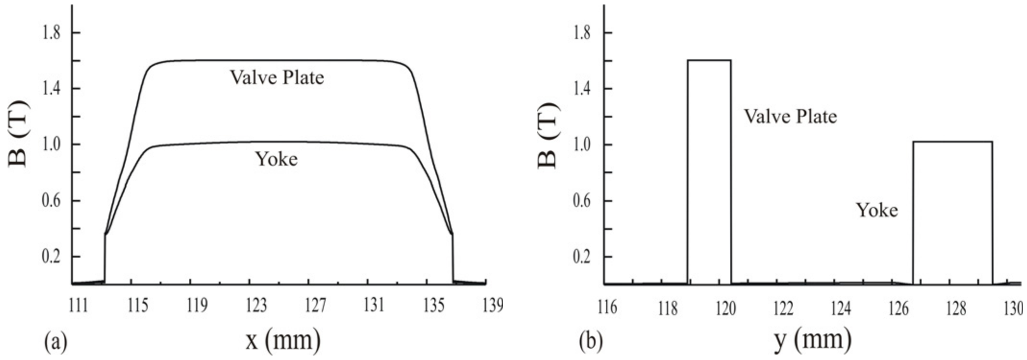

Figure 3. Effects of the valve plate thickness TV on magnetic field distributions in the yoke and the valve plate (a) along the lines ab and ef respectively and (b) along the line cd shown in figure 2; TV=1.5 mm.

valves under multibillion cycle operation. The rate and magnitude of this wear seems to be dependent upon the material and geometric parameters, some of which (e.g. mass, size) affect the dynamic performance parameters (e.g. velocity, acceleration, mechanical response time). To quantify this, a number of magnetic materials (such as Radiometal 4550, Armco, Hyperm 0, Hyperm Co50, etc.) have been investigated. Also, extensive modelling studies have been carried out to investigate the effects of geometric parameters. One of the aims here is minimise the thickness of the valve plate, TV (shown in figure 1).

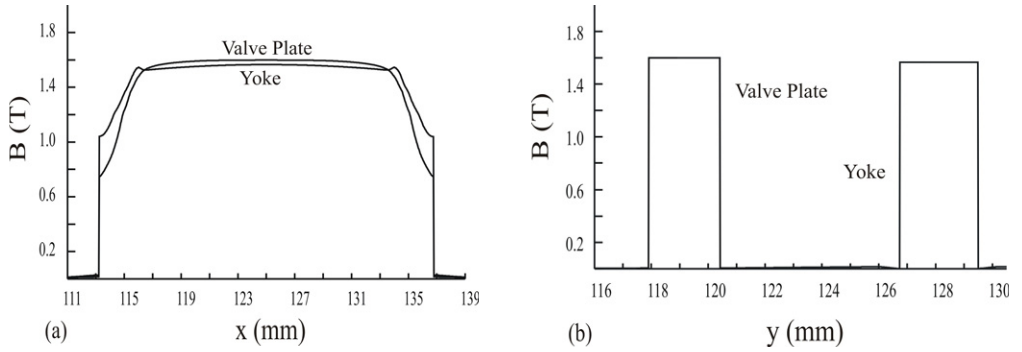

Figure 4. Effects of the valve plate thickness TV on magnetic field distributions in the yoke and the valve plate (a) along the lines ab and ef respectively and (b) along the line cd shown in figure 2; TV=2.5 mm.

Some of the modelling results are presented in figures 3-5, which show the effects of the valve plate thickness TV on the distribution of magnetic flux in the yoke and in the valve plate along the lines ab, cd and ef, shown in figure 2. These, together with the magnetic force versus valve plate thickness, F=f(TV) curve, presented in figure 5 show that the force (an important design parameter) is not only strongly dependent upon the thickness of the valve plate but also on the relative levels of saturation in the yoke and the valve plate. The maximum force is obtained for the valve plate thickness values between 2.5-2.75 mm, which correspond to almost identical levels of saturation in the yoke and in the valve plate (figure 4).

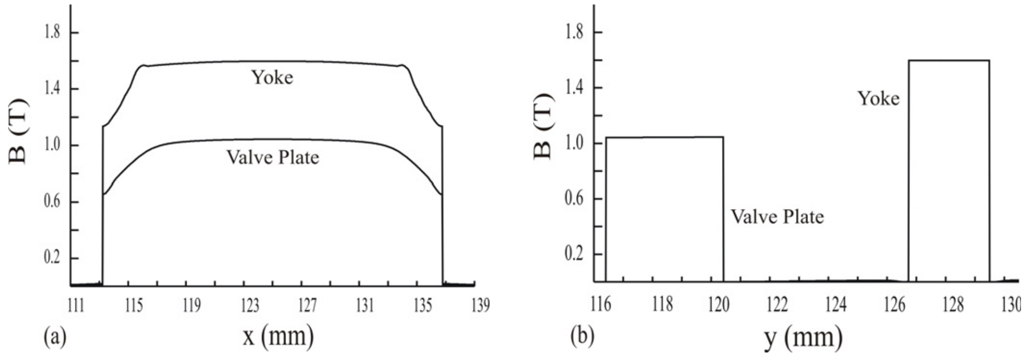

Figure 5. Effects of the valve plate thickness TV on magnetic field distributions in the yoke and the valve plate (a) along the lines ab and ef respectively and (b) along the line cd shown in figure 2; TV=4 mm.

3.2. Thermal modelling and its validation

As discussed earlier in Section 2, the EM ejector valve investigated in this work poses a unique set of thermal problems because of its small size, high frequency of operation, continuous duty cycle and the very compact packaging in a linear array with many other ejector valves. In addition, the primary mechanism of sinking of heat produced in the ejector valve by the high pressure compressed air which the valve is meant to ‘switch’, also constitutes a challenge for adequate thermal modelling. Various modelling investigations were carried out to investigate the thermal behaviour of the above ejector valve using 2D FE models. Some of the results have been compared with the corresponding experimental data, which in general, shows good agreement (figure 7). The experimental data presented in figure 7 were obtained for those cases when there was no air cooling by the compressed air. Although this does not constitute a normal mode of operation, at higher currents the loss of air cooling causes significant over-heating of the excitation coil, resulting in its thermal failure after several minutes of operation (curve 5 in figure 7). Since all the modelling and experimental studies were carried out on single isolated ejector valves, this situation is likely to worsen for valves which are compactly packaged together.

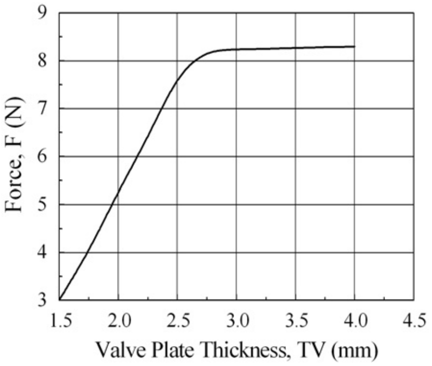

Figure 6. Variation of magnetic force F with valve plate thickness TV for a given excitation current.

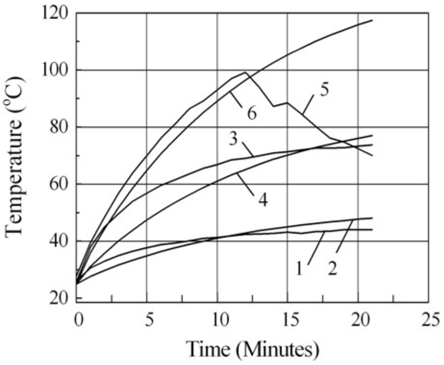

Figure 7. Experimental validation of thermal modelling results for various excitation currents I: 1, 3 and 5 – experiment, 2, 4, 6 – modelling; 1, 2 – I=1 A, 3, 4 – I=1,5 A, 5, 6 – I=2 A.

4. Conclusions

Finite element modelling methodologies have been developed for the design and investigation of electromagnetic and thermal behaviours of high-speed, large-force and long-lifetime solenoid actuators used as pneumatic ejector valves in optical sorting machines for bulk food sorting. The actuator designed so far has been shown to have performed between 1-2 billion cycles under life and field trials. To our knowledge no other EM actuator with similar requirement specifications is capable of matching this performance. It is believed that the above design is pushing the limits of performance that can be achieved by actuators based on the EM solenoid principle. Work is continuing on the further development of the models discussed and their use in actuator design and optimisation.

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