Development of Linear Pulse Motor Type Control Element Drive Mechanism for SMART

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Abstract

The system-intergrated modular advanced reactor (SMART) currently under development at the Korea Atomic Energy Research Institute is being designed with soluble boron free operation and the use of nuclear heating for reactor start-up. These design features require a Control Element Drive Mechanism(CEDM) for SMART to have fine-step movement capability as well as high reliability for fine reactivity control.

In this paper, the design characteristics of a new concept CEDM driven by a Linear Pulse Motor (LPM) which meets the design requirements of the integral reactor SMART are introduced. The primary dimensions of the linear pulse motor are determined by electro-magnetic analysis and the results are also presented. In parallel with the electro-magnetic analysis, the conceptual design of the CEDM is visualized and checked for interferences among parts by assembling three dimensional (3D) models on computer.
A prototype of the LPM with double air-gaps for the CEDM sub-assemblies to lift 100kg is designed, analysed, manufactured and tested to confirm the validity of the CEDM design concept. A converter and test facility are manufactured to verify the dynamic performance of the LPM. The mover of the LPM is welded with ferromagnetic material and non-ferromagnetic material to get the magnetic flux path between the inner stator and outer stator.

The thrust forces of LPM predicted by the analytic model have shown good agreement with experimental results from the prototype LPM. It is found that the LPM type CEDM has high force density and a simple drive mechanism to reduce volume and satisfy reactor operating circumstances with high pressure and temperature.

1. Introduction

SMART is being developed for a multi-purpose nuclear power plant for electricity generation or seawater desalination. Reactivity of the integral reactor SMART is controlled by rods.

The Reliability and safe operation of a nuclear power facility during its whole service life depend on many factors. Among those primary importance is given to failure-free performance of the Core Protection System (CPS) of which an important component is the control rod drives. The CEDMs are intended to move the Control Element Assembly (CEA), to retain them in demanded position in all normal operation modes and also to introduce them into the core as emergency protection comes into action. The modes of CEDM operation (movement at preset speed or holding) are determined by the signals from the CPS [1].

The main engineering solutions listed below are taken as the basis of the CEDMs design:

- In case of emergency, CEAs are to be introduced into the core from any position (CEDMs are designed to be capable for insertion even if no actuating power sources are available to the CEDM or CPS as a whole);
- Generation of CEA position signals;
- Kinematic link between CEA and position indicator;
- Provision of CEA motion within a limited travel in a standard control mode and generation of signals on its position;

All assembly units and components have in contact with the primary coolant are made of corrosion-resistant steels and alloys undergone operation testing in the operating facilities.

2. System descriptions

The CEDM consists of a Linear Pulse Motor (LPM), CEA position indicator, hydro-damper, and Extension Shaft Assembly (ESA) connecting CEDM and CEA. Section view of SMART CEDM is shown in Figure 1. Casing of LPM are made with the use of welded joints. The CEDM separate units are joined to each other by flanges with studs and nuts. The CEDMs are located on the reactor central cover and connected to it by means of thread and omega seal weld. Communication lines between each CEDM and control hardware are provided by cables.

2.1 Linear Pulse Motor

A linear pulse motor is used in the CEDM for SMART [2]. Such CEDM has a number of considerable advantages as compared with the CEDMs with other motors:

- Simple kinematic scheme;
- High operational reliability;
- Long service life;
- Rather small overall dimensions;
- Low cost;

Drawbacks of the linear pulse motor (e.g., low efficiency, relatively more complicated control system as compared with DC motor) are not an obstacle for applying such a CEDM for SMART. A linear pulse motor (LPM) is a four-phase synchronous electric DC machine with a passive rotor in a coolant medium inside a strong sealed body made of magnetosoft corrosion-resistant steel. The stator and rotor are the basic units of the LPM. In turn, the stator consists of two parts: outer and inner.

An outer stator is a strong leak-tight cylindrical casing made of alternating portions of magnetosoft and nonmagnetic corrosion-resistant steels. Over the inside casing there are 4 annular groups with 8 teeth in each group over the portions of magnetosoft steel. Graphite bearings guiding LPM armature along the outer diameter are placed between the groups. 16 coils made of heat-resistant wire and magnetic circuits made of magnetosoft steel with non-magnetic spacers are placed outside the stator frame.

An inner stator is a structure of cylindrical form made of alternating portions of magnetosoft and nonmagnetic corrosion-resistant steels on the outer surface. The rings of nonmagnetic corrosion-resistant steel are placed between the teeth. The inner stator's teeth are located strictly opposite the relative teeth of the outer stator. The teeth of both outer and inner stators are not displaced with regard to one another. Graphite bearings guiding LPM armature along the outer diameter are placed between the annular groups. The inner stator is held inside the outer stator by means of attachment of its inner tube to the lower part of the LPM.

The LPM rotor is made in the form of tube also with alternating portions of magnetosoft and nonmagnetic steels.

Figure 2 shows a section view of the LPM and the magnetic flux path when the coil is energized. The coils of two LPM adjacent phases, for instance I and II, are alive at any instant. As a control command comes to the LPM control unit, the LPM phase I gets off and phase III gets on, after that phase II gets off and phase IV gets on, etc. Forces of magnetic interaction tending to arrange teeth opposite to each other occur between stator teeth and appropriate rotor teeth of the LPM phases are switched on. Since the teeth of each rotor phase are made with a displacement with regard to the teeth of neighbouring stator phases, then at each switch a torque will occur tending to move a rotor also by 4 mm. As LPM phases are commutated in the sequence I-II, II-III, III-IV, IV-I, I-II and so on, the rotor will move in one direction, but with the sequence I-II, IV-I, III-IV, II-III, I-II and so on, it will move in another direction. If commands do not come to the control unit, the LPM rotor remains stationary.

2.2 Position Indicator

Each CEDM includes four(4) reed switch position transmitters (RSPT). The RSPTs provide a stepped analog output signal proportional to the CEA position within the reactor core. The analog position transmitter consists of a voltage divider network suitable for use with an external power supply of 15 VDC. The analog transmitter is composed of precision resistors and magnetically actuated reed switches. The position transmitter analog output signal range is from 5 to 10 volts, which corresponds to the full mechanical travel of the CEA. The analog output signal is step-wise linear and continuous over this range.

The RSPT provides discrete output contact closure at positions corresponding to the upper limit and lower limit of CEA travel [3,4].

2.3 Damper

While emergency protection is actuated, the CEA and CEDM mobile components will have a considerable kinetic energy reserve. If a damping device is not envisaged in the CEDM design for absorbing this energy, the CEDM kinetic circuit components will experience dynamic overloading by the end of the working travel, which may result in mechanical damages.

In terms of operation principles, dampers may be of magneto-inductive, pneumatic, friction, spring, hydraulic type and so on. Keeping in mind that the CEDM mobile components are continuously submerged in the primary coolant environment, the CEDM is provided with a hydraulic damper as the simplest and most reliable. As it comes into action, the kinetic energy of the CEA and the CEDM mobile components is converted into thermal energy and dissipates into the environment.

A hydraulic damper (hereinafter refer to as hydrodamper) incorporates: cylinder, piston, sealing rings made of graphite fluoroplastic material (they also play the role of plain bearings), coiled compression spring and a set of disk springs. On the piston surface there is an inclined groove which together with the plain bearing forms a hydraulic throttle (slot of variable section).

While the CEA moves between the LLS(Lower Limit Switch) and ULS(Upper Limit Switch) the hydrodamper does not affect CEDM operation because the CEDM mobile components do not get into contact with the hydrodamper piston. During this period of time the coiled spring of the hydrodamper holds up its piston at a mechanical rest in the lower position, the inner cavity between the cylinder and piston has a maximum volume.

The principle of hydrodamper operation is as follows. When the CEA gets into the core in response to an emergency protection signal, the CEDM mobile components will get in contact with the piston by the end of working travel and start moving it into the cylinder. The piston travel will be hampered by two forces, i.e. springs effort and hydraulic resistance force which grow as travel proceeds.

As far as water is almost incompressible, it will get out through a hydraulic throttle creating counterpressure in the inner cavity of the hydrodamper that will provide a braking effect upon the CEDM mobile components. The higher the water speed and smaller the throttle section, the higher the friction effort. At the initial instant of the hydrodamper operation the throttle section is maximum and the fraction of hydraulic resistance in the damper braking effort is relatively small. The value of the braking effort is determined by the effort of the spring preliminary compression.

As the piston travels, the throttle section gets smaller but the braking effort gets larger. By the travel end the throttle slot section will become minimum and the speed of mobile components in CEDM will get down to zero.

2.4 Extension shaft assembly

Tie ESA is an intermediate link between the CEDM armature and CEA. ESA is designed as two aligned thin wall tubes made of corrosion-resistant steel. Outer tube is the ESA in itself, while inner tube serves to manipulate the chuck placed at the lower end of the ESA. Chuck engages with the hub placed at upper part of CEA.

3. Development of LPM

Linear pulse motors (LPMs) are electromechanical devices that convert pulse inputs to incremental motion outputs. When properly controlled, the number of linear steps of the motor equals that of input current pulses. In the past, although LPM was to operate simply and have a lot of advantages, it had applications for short stroke linear motion step drives and low output linear drives. But recently according to the advances in power electronics, semiconductor switching elements and microprocessor controllers, LPMs are being used in industrial applications widely. Also due to the advances of manufacturing techniques, LPMs can be adopted for the CEDM in SMART.

The new design method to optimize the shapes of the teeth, slots and mover to produce maximum thrust force is proposed. Finally we compared a calculated static thrust force with an experimental static thrust force.

3.1 Theory of thrust force

The magnetic energy, W_m and the magnetic coenergy, W_{co} stored in magnetic fields are as follows; respectively given by [5]

$$W_m = {}_{V} {}_{0}^{B} H(B)\ dBdV \tag{1}$$

$$W_{co} = {}_{V} {}_{0}^{H} B(H)\ dHdV \tag{2}$$

In terms of coenergy the expressions for the force can be written as

$$F_x({}_{d}, x) = \frac{W_{co}}{x} \Bigg|_{{}_{d}=const.} \tag{3}$$

where ${}_{d}$ is magnetomotive force(MMF) in the air gap d.

The magnetic coenergy, W_{co} is, from eq. (2)

$$W_{co} = \frac{B^2}{2m_0} d\ x\ l \tag{4}$$

where l = the length of model. m_0= permeability of free space. The flux density in the air gap is as follows:

$$B = m_0 \frac{{}_{d}}{d} \tag{5}$$

The magnetic coenergy, W_{co} is derived from eq. (4) and eq. (5) as

$$W_{co}({}_{d}, x) = \frac{m_0\ {}_{d}^{2}}{2d} x\ l \tag{6}$$

Thus the mechanical force F_x is obtained from eq. (3) and eq. (6).

$$F_x = \frac{m_0}{2d}\ {}_{d}^{2}\ l \tag{7}$$

The mechanical force F_x is proportional to ${}_{d}^{2}$ and inversely proportional to air gap length.

For motoring action, the current must be turned on when rotor position x is 0, 2t, 4t, 6t, … and must be turned off when rotor position$x$ is t, 3t, 5t, … .

Because of turning off position (x = t|- 2t, 3t|- 4t, 5t|- 6t), the average force F_{xavg} can be half the force of eq. (7):

$$F_{xavg} = \frac{F_x}{2} = \frac{m_0}{4d}\ {}_{d}^{2}\ l \tag{8}$$

If one refers the force per pole element to the active rotor surface in order to obtain some feeling for the magnitude of the force density F_{Ax} in LPM, then the surface force density F_{Ax} can be derived as [6]:

$$F_{Ax} = \frac{F_{xavg}}{2t\,l} = \frac{m_0}{8dt}\;{}^{2}_{d} \qquad (9)$$

In dealing with LPM, eq. (9) is very useful for basic design. The force density F_{Ax} is proportional to ${}^{2}_{d}$ and inversely proportional to air gap length and pole pitch.

3.2 Design

3.2.1 Specifications

We chose LPM with double air-gap to obtain high thrust force per unit volume and its teeth are constructed in the circumference direction. The magnetic path is composed of an outer stator, air-gap, mover, and inner stator, when the windings are magnetized. Then thrust force is generated by magnetic flux in the air-gaps [7].

To calculate the thrust force, we should use a 3-dimension model. But in this design we analyzed the LPM using a 2-dimension equivalent model. The 2-dimension model is shown in Figure 4 and design parameters are tooth pitch, tooth width, tooth height and outer/inner radius of the mover, outer stator and inner stator.

The table 1 shows the design requirements for LPM of SMART CEDM.

Table 1 Design requirement of LPM

Items		Value
Total stroke	[mm]	2,000
Displacement/pulse	[mm]	4.0
Operating speed	[mm/sec]	0-50
Load	[kg]	100
Holding force	[kg]	150
Dynamic thrust force	[kg]	100
Air gap	[mm]	Less than 0.4
Friction force	[kg]	20-30

3.2.2 Analysis

Using the finite element program (Flux2D), we calculated the distribution of magnetic flux lines as shown in Figure 5 when the stator teeth and mover teeth are aligned.

We also calculated the trends of thrust force density generated by the variation of the design parameters. The trend of the thrust force density varied according to the variation of the ratio of the slot width to tooth width, and according to the variation of mover height, and according to the variation of stator tooth height.

From the above calculated results, with consideration of the design specifications of Table 1, and constrained manufacturing and assembly conditions, we determined the design parameters of LPM in Table 2 for SMART CEDM.

Table 2 Designed parameters

Mover	Inner radius	59.7 mm
	Outer radius	72.3 mm
	Tooth width	6.0 mm
	Tooth pitch	16.0 mm
	Length	2,200 mm
Outer stator	Inner radius	73.5 mm
	Outer radius	84.0 mm
	Tooth width	6.0 mm
	Tooth height	4.0 mm
	Tooth pitch	16.0 mm
Inner stator	Inner radius	40.0 mm
	Outer radius	59.0 mm
	Tooth width	6.0 mm
	Tooth height	5.0 mm
	Tooth pitch	16.0 mm
Air-gap		0.35*2 mm
Number of phases		2-P bipolar

3.3 Manufacturing and test

The conceptual design of the LPM is visualized and checked for interferences among parts by assembling three dimensional (3D) models on the computer before manufacturing the LPM for SMART CEDM. Figure 6 shows the three-dimensional (3D) model of LPM that was completed by I-DEAS software. Trial manufacturing of the LPM of a new type CEDM with 4-phase coil was conducted and is shown in Figure 7. The LPM has such a complicated structure that many high level manufacturing techniques for its components should be adopted. The performance test of the LPM was carried out with the test facilities shown in Figure 8 to verify its design.

The calculated static thrust force of the designed LPM using FEM and experimented static thrust force to 1-phase coil are compared and shown in Figure 9. The measured thrust force is about 10% less than the calculated thrust force because many manufacturing processes induced the small air-gaps of joint parts. Figure 10 shows the experimental results of total thrust force of LPM. The performance achieved by LPM has been confirmed to be as good as its design target.

4. Conclusion

In the design of the integral reactor SMART, it is planned to develop CEDMs with fine-step movement capability as well as high reliability for fine reactivity control. An idea was proposed for a CEDM with a LPM that will fit best the integral reactor SMART and this basic concept was realized by magnetic analysis, 3D modeling and trial manufacturing of the LPM.

Achievements in this investigation include those of the following design and basic test.

- Detailed design to give concrete form to their structures with attention especially paid to the driving motor of the LPM which is the crucial component of the built-in type CEDM.

- Selection of tooth shapes of inner stator, outer stator and mover as the best option for specification by magnetic analysis. We chose structurally allowable design parameters.
- Confirmation of performance of electric and mechanical components through 3D model, manufacturing and tests.

The LPM for the CEDM of SMART requires high force density and a simple drive mechanism to reduce volume and must satisfy the reactor operating circumstances of high pressure and temperature. The results of this study have shown that a CEDM with LPM can be effectively applied to the SMART.

Acknowledgement

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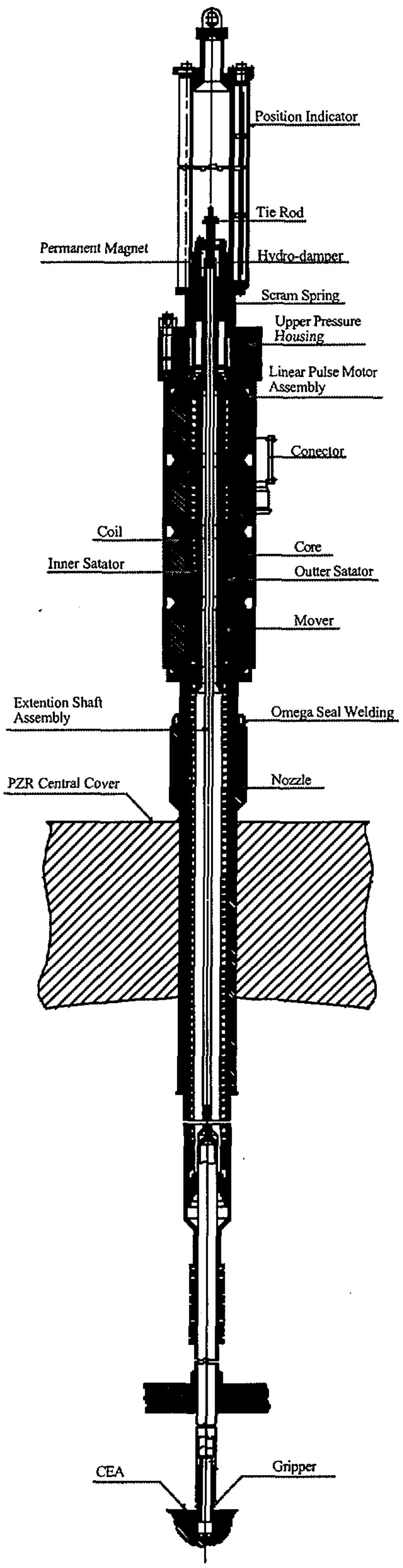

Fig 1. Section view of SMART CEDM

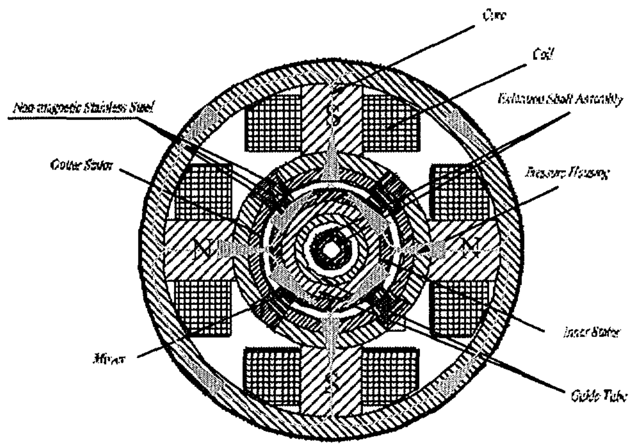

Fig 2. Section view of LPM

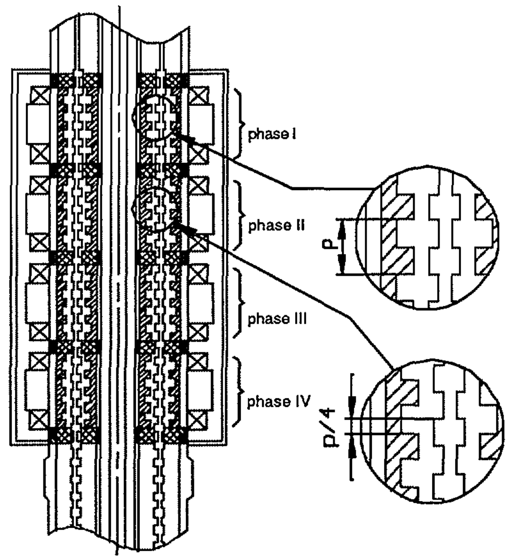

Fig 3. Pitch concept of LPM

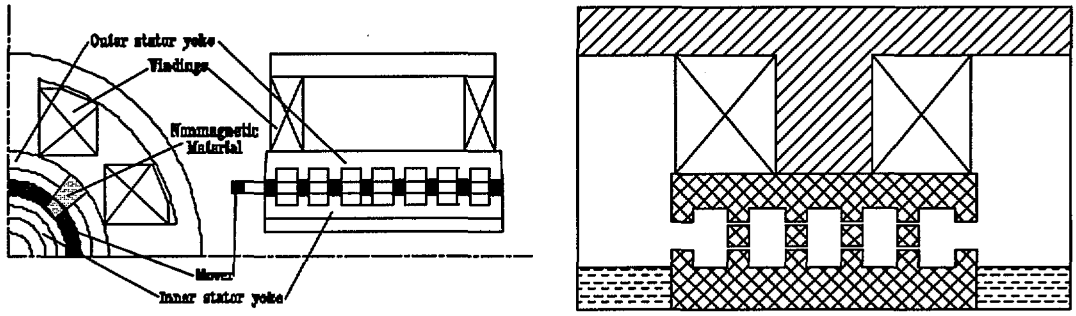

Fig 4. Equivalent 2-dimensional analysis model of LPM

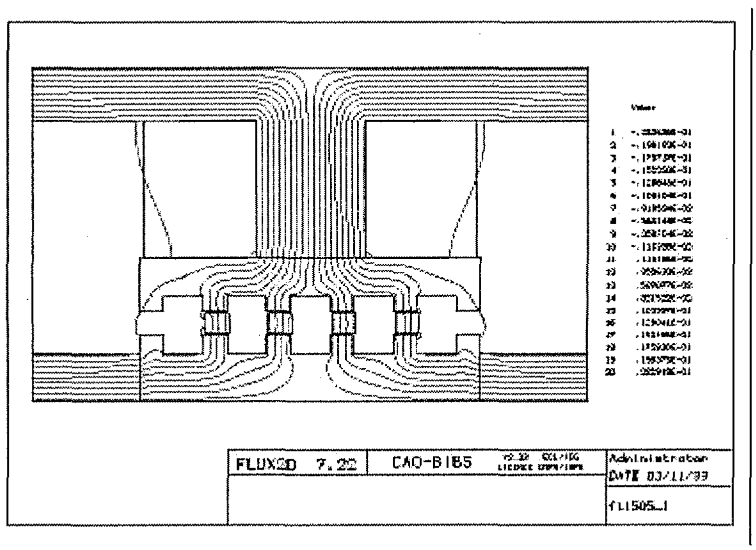

Fig 5. Equi-magnet flux line

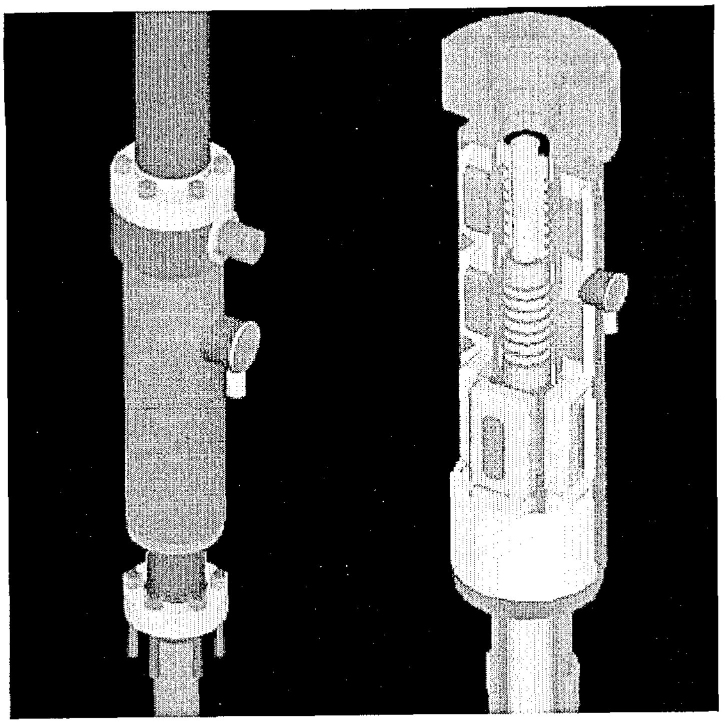

Fig 6. 3D model of LPM for SMART CEDM

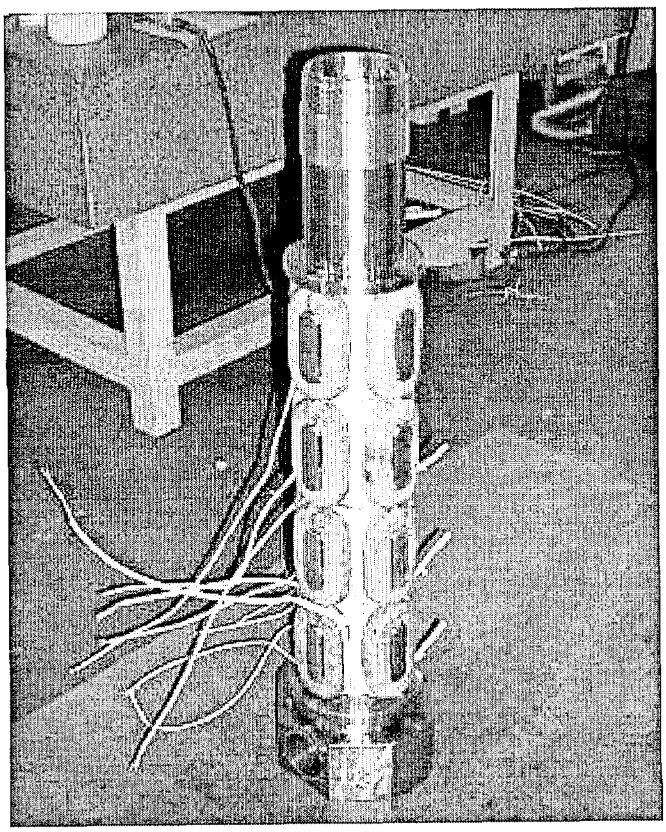

Fig 7. Photography of manufactured LPM for SMART CEDM

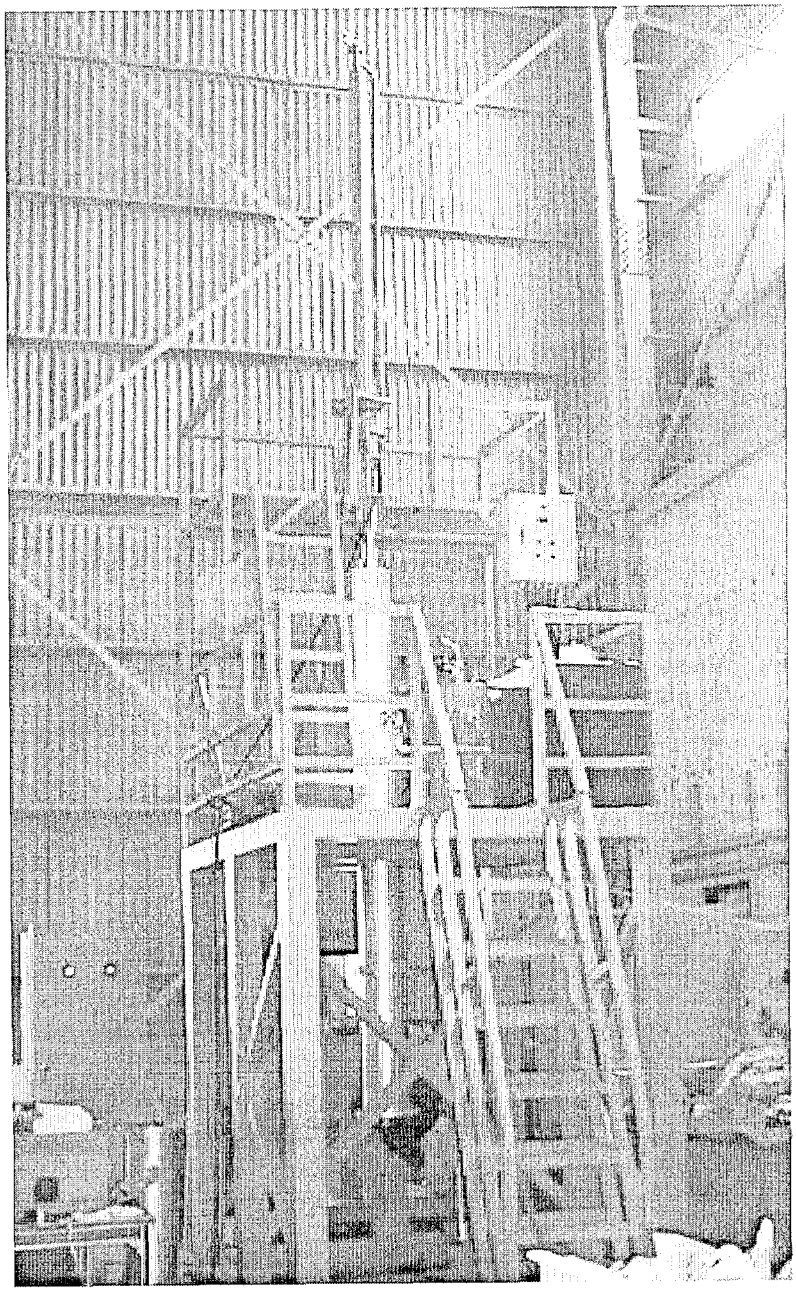

Fig 8. Photography of test facilities for LPM type CEDM

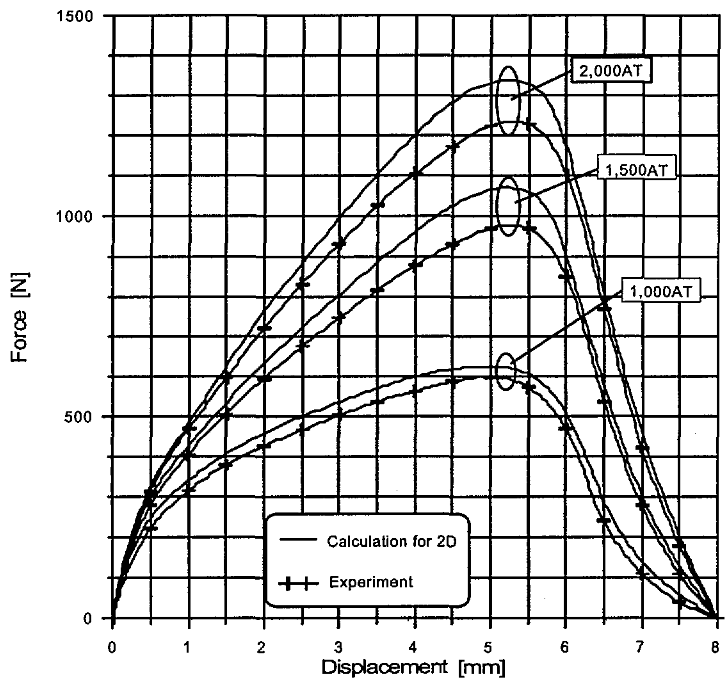

Fig 9. Experimental and calculated results of static thrust forces to 1-phase stator coil

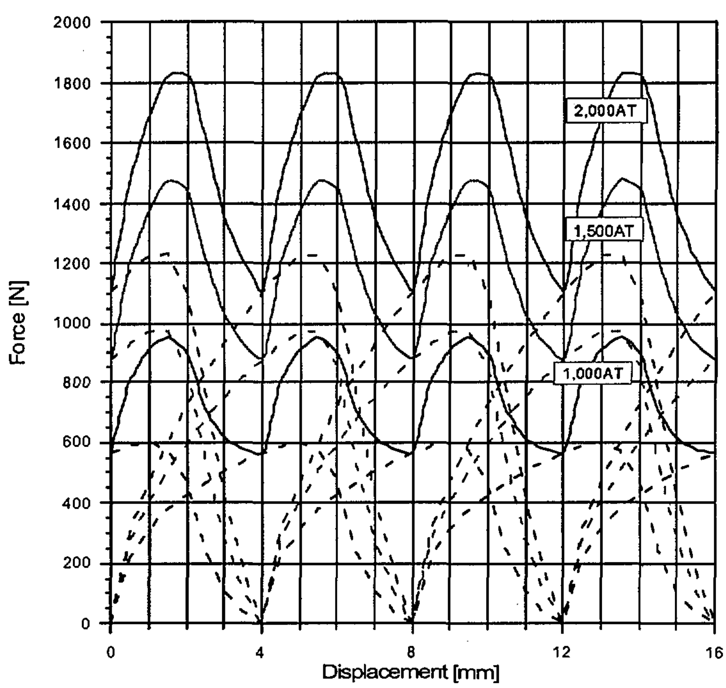

Fig 10. Experimental results of total thrust forces of LPM