# Electromagnetic Actuators as Artificial Muscles for a Robotic Motion ---Advantages and Limitations---

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**Abstract:** The authors are developing high thrust/torque electromagnetic machinery for direct drives with strong rare-earth permanent magnets and transversal flux configuration. The transversal-flux configuration enables significantly shorter pole pitch without substantial increase of leakage flux than longitudinal flux configuration applied in traditional electrical machinery. Higher power density per volume/weight is possible by the short pole pitch by applying input voltage in higher frequency in low speed drive. Consequently, a direct drive with high force/torque is possible, since the produced force is power/speed. Since a light and strong electromagnetic actuator will be useful for advanced robotic motion controls, this paper describes recent research and development efforts for such low speed/ high force electromagnetic synchronous machines.

*Keywords:* electromagnetic actuator, linear motor, permanent magnet, high thrust, motion control

## 1. *Introduction*

An engineering application of life-mechanics based on usage of actuators corresponding to bi-articular muscles[1] to artificial robotic arms/legs is a significant subject in this workshop. It may be one of the most important contribution of medical/engineering cooperation for realizing an inherently simplified and efficient control algorithms real time  for real-time motion control of robotic arms/legs, whose dynamic motion of equations are substantially complicated. Earlier studies, which demonstrated natural jumps and walks with relatively simple structures using springs and/or hydraulic actuators showed possibilities of the theory and attracted sober interests of experts not only in engineering fields but also in societies of medical researchers and physical therapists[2][3]. When electromagnetic actuators can be directly used as artificial substitutions of bi-articular muscles, the fast and precise controllability of electromagnetic machines will be an inherent impact for high performances of the motion control. On the other hand, inevitable mass and local heating of the electromagnetic actuators are technical obstacles for the application. Recent synchronous motor technologies may solve the difficulties. This paper, therefore, reviews the advantages and problems of synchronous machines using strong rare-earth permanents magnets and transversal flux concept[4].

## 2. *Advantages and problems of electromagnetic actuators*

### *2.1 Electrostatic/electromagnetic field energies stored in unit volume and actuator forces*

The upper limitation of outputs of actuators basically depends on stored field energy per volume. For instance, the electrostatic energy stored in unit volume is as follows when homogeneous electrostatic field $E = 3\times10^5$ V/m is applied:

$$W_e = \frac{\varepsilon_0 E^2}{2} = 3.98\times10^{-1}\ \mathrm{J/m^3} \qquad (1).$$

In comparison, electromagnetic energy in the same volume is as follows when the homogeneous electromagnetic flux density $B = 1.3$ T is applied:

$$W_m = \frac{B^2}{2\mu_0} = 6.72\times10^5\ \mathrm{J/m^3} \qquad (2).$$

This obvious difference is the reason why almost all the actuators in ordinary size are electromagnetic ones, and electrostatic actuators are used just for smaller applications.

By the way, $\mathrm{J/m^3}$ can be read also as $\mathrm{N/m^2}$ in (1) and (2), that is the unit for pressure, or force density per cross-section of a "flux tube". The equations in (1) and (2) is also the forms of the normal component of electrostatic/electromagnetic Maxwell's stress tensor. (2) corresponds to approximately 7 atom, that means the upper limit of electromagnetic normal attractive force per surface to be produced by ordinary-temperature electromagnetic actuators.

### *2.2 Recent permanent magnet motors*

It is necessary to realize large flux density in magnetic gap in an electric machine without applying large electric currents to its windings for an efficient and high force drives. Therefore, strong rare-earth magnets are often used in recent motors in industrial applications and servo-controls.

### *2.3 Problems of electromagnetic actuators*

Electromagnetic actuators have the advantages of

(A) the possibility of local actuation where the actuation is requested,
(B) flexibility in designing controlled dynamic behaviour, and
(C) quality of the precise and motion repeatable controls.

On the other hand, they have problems of limited force and local heating.

One usual solution for obtaining large force is to apply mechanical reduction gears for converting rotational speed of high speed electrical machines. Another way may be to enhance the energy amount stored in magnetic field per volume by applying large electromotive force by using superconducting technology and omitting ferromagnetic cores to be saturated from the magnetic circuit. The first solution has been preferred and often applied in present robot hardwares. Contrarily, the second one has difficulty in practical installation. For emulating the functions of bi-articular muscles, especially for representing dynamic property of flexible and viscous behaviours, direct drives without any mechanical speed conversion are preferred. An electric machine which can produce directly strong force is requested in this sense.

### *2.4 Technology of large thrust/torque and direct drives*

When the energy amount stored in field per volume is fixed, realization of low speed drive under electric power supply with high frequency is the unique way for obtaining large thrust/torque. Design of a permanent magnet synchronous machine with substantially short pole pitch without increase of leakage flux is the key for fulfill the requirement. Prof. H. Weh[4] proposed the "Transversefluxmaschine" from this point of view. The early version of his test machine is shown in Fig. 1. The characteristics of the machines are summarized and compared with conventional AC-machines. Because the thrust/torque is a tangential component of the magnetic force in (2), the thrust density per surface, described in the third in Table 2, can be typically utmost several percent of the amount calculated in (2) in conventional AC-machines. Weh writes in [4] numerical examples. Even with the newest and strongest rare-earth magnets, longitudinal flux machines realize just 12% of the force-density of (2). In contrast to this, his transversal flux type machine can generate from 15 through 35% of the amount in (2).

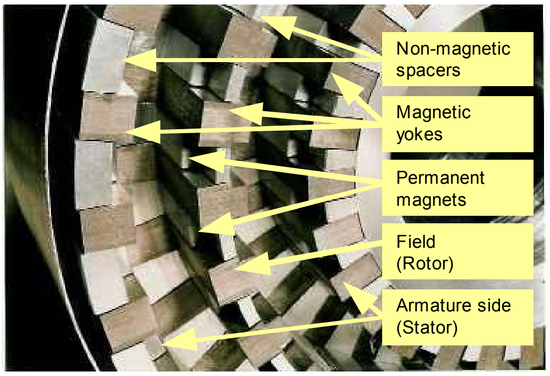



Fig. 1 The first prototype transversal flux-motor tested at the Technical University in Braunschweig in 1989.

The middle part in Fig. 1 is a rotor consisting of rare-earth permanents magnets and supporting frame made of non-magnetic metal. The machine has double-side armatures. Each side has transversal magnetic yokes which are magnetically excited by armature ring windings. Since the left and right armature sides are excited by two separated ring windings, it is a two-phase AC system, whose phase shift between one and another phases is $\frac{\pi}{2}$. Since the configuration allowed torque density several times higher than conventional ones, this type of machines was intensively studied in European research institutes in 1990's. However, the structure and installation are significantly complicated, and it was an obstacle for wide industrial applications.

TABLE 1. Comparison of longitudinal and transversal flux-type AC machines (according to Prof. Weh's summary in [4] ).

| Longitudinal flux-type induction motors, synchronous motors (conventional types) | Transversal flux type synchronous machine (proposed type) |
|---|---|
| Distributed multiple phase AC windings in axial slots | Concentrated and separated ring windings |
| Longitudinal flux loops for generating traveling/rotating magnetic field | Series of short transversal flux loops |
| Pole pitch larger than 3cm | Pol pitch shorter than 3cm |

TABLE 2 Evaluation of machine performance

| Performance index | Unit |
|---|---|
| Power density per mass | kw/kg |
| Torque density per mass | Nm/kg |
| Torque density per volume | $Nm/m^3$ |
| Torque density per surface | W/Nm |
| Energy loss per torque | $kgm^2/Nm$ |

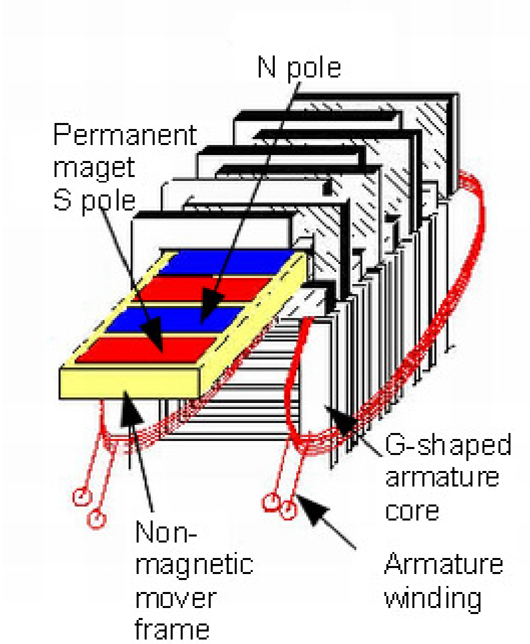



Fig. 2 Tunnel actuator proposed by Kim, Hitachi Ltd. Corp.

### *2.5 Recent variations studied in Japan*

The second author, Dr. H. J. Kim, proposed a kind of variations of transversal flux type linear motor during his research works at Hitachi Ltd. Corp. as shown in Fig. 2. He demonstrated quick motion with significantly high acceleration and precise positioning[5]. Since the mover, consisting of permanent magnets and nonmagnetic plate frame, is bookended by the armature G-shaped cores, the normal attractive force, which usually causes difficulty in mechanical support of the mover, can be inherently compensated and suppressed small. Also the configuration is relatively simple, and the engineering installation is much easier than the types of original transversal flux machines. The linear motors were named "*Tunnel Actuators*" and they were applied to machine tools, to which quick motion, precise positioning and light engineering maintenance works are requested. Fig. 3 shows one of early prototype motors applied to industrial machine tools. After his leaving and starting his own motor manufacturing company, *Sungjin Royal Motion Co., Ltd.* in Korea, he extends the engineering philosophy and developing new transversal flux type linear synchronous motor series, to be named as *Royal Motion actuator*.

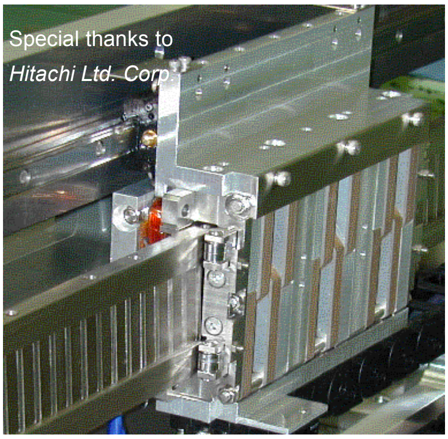



Fig. 3 An early prototype of the Tunnel Actuator developed for industrial machine tools.

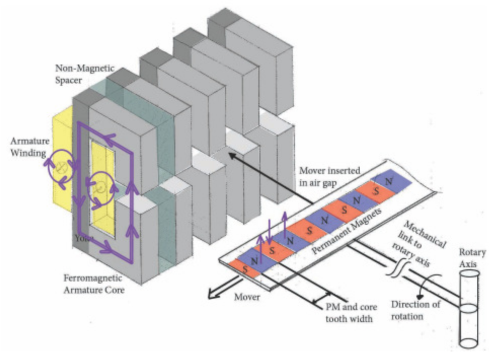



Fig. 3 Fundamental diagram of a rotary transversal flux motor extended from tunnel actuators being developed by Koseki.

The first author, Koseki, continues joint research activity with Hitach Ltd., for developing a rotary disk synchronous machine. The basic configuration of the armature stator and a rotor with permanent magnets is illustrated in Fig. 4. Fig. 5 shows a photograph of the second prototype machine. Although the second machine proves the torque density, 100kNm/m$^3$, the present performance is not satisfactory yet. Torque loss and partial heating, probably caused by unexpected eddy currents in supporting metal frames, shall be analysed and eliminated in further studies. Also an appropriate design of magnets' pole pitch shall be studied as a compromise between leakage flux and torque density.

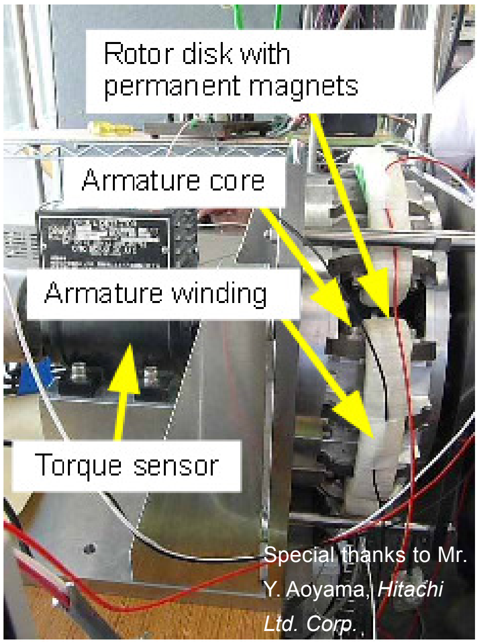



Fig. 5 The second prototype of the disk-rotor transversal flux synchronous machine at the University of Tokyo.

### *2.6 Actuator control*

Force, speed and position controls of an industrial motor are designed based on the established cascaded feedback loops. They are fundamentally "stiff" controls. Contrary to them, human/life-emulating motion controls request flexible motion and other methodologies in gain-tuning. An idea for such motion control is discussed by Fukusho in [6]. Fast, repeatable and accurate force production of electromagnetic actuators are useful for such different requests in motion controls.

## *3. Electromagnetic actuators for emulating motion of a living body*

### *3.1 Fundamental concepts*

Intending to apply electromagnetic actuators to emulate motion of a living body, we assume the following requirements to an electromagnetic actuator.

(1) Whereas each muscle of an antagonistic pair of muscles only shrinks, an electromagnetic actuator can produce force in both direction.
(2) Dynamic property of an actuator, *i.e.,* stiffness and viscosity of it, can be arbitrarily designed and set through active electric controls.
(3) Antagonistic motion shall be selectively applied if appropriate.
(4) Stiffness of the actuator is controlled proportional to the steady load force.
(5) An antagonistic pair of muscles shall be basically substituted by an electromagnetic rotary motor or a linear actuator, to which the stiffness/viscosity-

controls described in next section is applied.

### 4. *Transversal flux linear synchronous machines as a substitute of an antagonistic pair of bi-articular muscles*

A linear synchronous actuator of strong thrust with reduced weight and volume is requested for the application. The article [6] discusses another possibility to emulate the function of bi-articular muscle pair virtually without any linear actuators by applying three to two coordinates transformation to the two rotary motors attached to shoulder and elbow joint.

### 5. *Virtual stiffness and viscosity control of an electromagnetic synchronous actuator*

Virtual stiffness and viscosity design of an electromagnetic actuator in Fig. 7 is possible by setting low gains to feedback controllers for conventional industrial force control[7] . Examples of tested behaviour are shown in Fig. 8, where the natural angular frequency is designed $\omega_n = 15\text{rad/s}$ and the damping factors $\zeta$, corresponding to the viscosity, are changed as parameters. The experimental results shows damping larger than expected in Fig. 8 (a). Preliminary experiments using the rotary machine in Fig. 4 show losses and local heating much larger than initial expectation caused by eddy currents in conducting parts of the rotor. The reason for the damping factors in Fig. 8 (b) larger than initial calculation in (a) may be this additional eddy-current loss in transversal flux configuration. Analysis of the loss and design improvement for suppressing the eddy current shall be furthermore investigated.

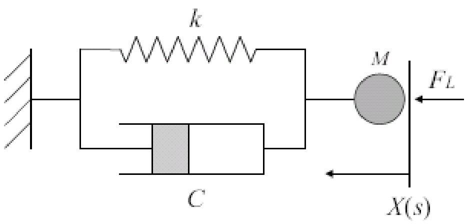
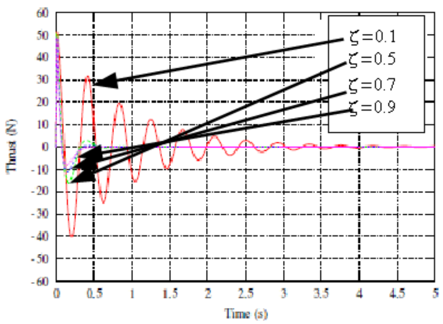
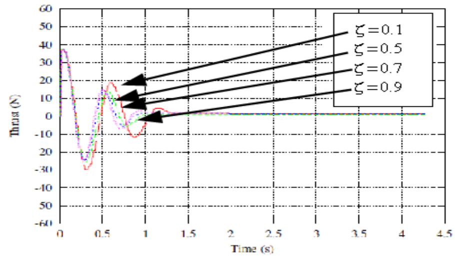



Fig. 7 A mechanical dynamic system to be emulated through a force-control-type stiffness/viscosity control.




(a) Simulated thrust responses.




(b) Measured thrust responses.

Fig. 8 Stiffness/viscosity- control results

($\omega_n$=15 rad/s *const.* with various damping factors $\zeta$)

### 6. *Conclusions and works in future*

We are presently trying to implement the control strategy of a bi-articular muscle and to show substantial advantage of the control method by applying an appropriate coordinates transformation to two rotary motors at joint in [7]. Separately to this discussion, we are trying to enhance the performance of a transversal flux synchronous machine. If the trial is successful in reducing eddy current loss and in enhancing the torque per volume, the achievement may contribute to the direct implementation of an electromagnetic actuator as a substitute of bi-articular muscles.

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