

# Specific Index Parameters Definition for Quantitative Evaluation of the Dynamic Performance of the Electromagnetic Mechanism Topologies within Controllable Actuators

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## Abstract

*Fast electromagnetic drive mechanism shows broad application prospects in many areas, but there is still a lack of unified evaluation parameters as to evaluate the dynamic characteristics due to diversity and complexity of the mechanisms. Three interrelated evaluation parameters are presented for topology analysis, namely the electromagnetic force sensitivity coefficient, the initial time constant and the sensitivity contribution coefficient. The specific parameters based evaluation can provide a basis for structural performance assessment as well as topology optimization. Comparison between the dynamic parameters of the discoid repulsion mechanism and the solenoid thrust mechanism shows that, the discoid one is superior to the solenoid one. The proposed research is to establish a general methodology for topology analysis and optimization of the electromagnetic mechanisms.*

**Keywords:** fast electromagnetic drive mechanism, evaluation parameters, electromagnetic force sensitivity coefficient, initial time constant, sensitivity contribution coefficient

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## 1. Introduction

Fast electromagnetic drive mechanisms are sighted of broad application prospects in many technical fields of the power systems [1], such as hybrid solid state switches [2], integrated fault current limiting devices [3-4], power quality issues [5-6] and phase control switches [7]. The operation principle of this mechanism is based one a pre-charged capacitor to discharge to a closing or tripping coil, resulting in a few milliseconds of the pulsed current. The moving coil which is fixed to the mechanical linkage is driven by the pulsed electromagnetic thrust force to achieve a rapid closing or breaking of the switch [8]. Currently, the main topologies of the coreless coil structure include the discoid repulsion mechanism [9] and the solenoid type thrust mechanism [10]. Many researchers have carried out theoretical and experimental studies on different topologies, however, it is difficult to make a choice among the different structural forms because of the lack of a generalized evaluation criteria. Evaluation of the traditional electromagnetic mechanism topology is mostly based on static indicators, which is difficult to assess the dynamic characteristics of the mechanisms. In this paper, a number of unique evaluation parameters are proposed for assessment of the fast electromagnetic mechanisms as to present a guiding line for further exploration of novel topologies and their optimization.

## 2. Electromagnetic Force Sensitivity

The traditional electromagnetic mechanism generally uses the rated power  $P=I^2R$  to denote its sensitivity. This index is only from the required energy point of view with the mechanism movement, which can not reflect the actual sensitivity of the electromagnetic control of the mechanical systems in the operating process. In fact, the flux, the electromagnetic force, moving speed and the other parameters can be used to describe the motion process of the electromagnetic mechanisms from different view angles, and these parameters are interrelated

to each other. According to the theory of sensitivity analysis, one of these interrelated parameters may be used to describe the sensitivity of the electromagnetic mechanisms without losing generality. From the kinematics point of view, the fundamental motion Equations for analyzing the electromagnetic mechanisms are given by

$$\begin{cases} F_e - F_L = m \frac{dv}{dt} & \text{(a)} \\ T_e - T_L = J \frac{dw}{dt} & \text{(b)} \end{cases} \quad (1)$$

where, Equation 1a corresponds to the linear motion while Equation 1b corresponds to the rotational motion, which in essence are consistent, with only difference in reflected forms.  $F_e$ ,  $F_L$ ,  $m$  and  $\frac{dv}{dt}$  refer to the electromagnetic force of linear motion system, the resistive force, the mass and acceleration of the motion parts, respectively.  $T_e, T_L, J$  and  $\frac{dw}{dt}$  denote the electromagnetic torque of rotational motion system, The resistive torque, the inertia and the acceleration of the rotating parts, respectively.

It can be seen that, the electromagnetic force generated by the mechanism as a driver can directly change the motion state of the mechanisms, however, regarding the electromagnetic mechanism, the control of the electromagnetic force is similar to the control of the power systems. Therefore, analysis of the sensitivity of the electromagnetic force can reflect the dynamic performance of the mechanisms, which is of significance to the design and control of the electromagnetic mechanisms.

Multiple mechanism topologies should be considered for electromagnetic force sensitivity analysis. Without magnetic saturation, the electromagnetic force produced within a mechanism can be obtained based on Maxwell 's electromagnetic force Equation, namely

$$F_e = \frac{1}{2} (iN)^2 \frac{\mu_0 S}{\delta^2} \quad (2)$$

where,  $F_e$  is the electromagnetic force,  $i$  is the coil current,  $N$  is the number of coil turns,  $S$  is the cross-section area of the moving iron core and  $\delta$  is the air gap length. The fixed coil and moving coil, for either the discoid repulsion mechanism or the solenoid type thrust mechanism, are connected in series so that the same current flows through the coils. The electromagnetic force can be expressed as

$$F_e = i^2 \frac{dM}{dx} \quad (3)$$

where,  $F_e$  is the electromagnetic force,  $i$  is the coil current,  $M$  is the mutual inductance between the fixed and moving coils. It can be seen from Equations 2 and 3, the electromagnetic force is proportional to the square of the current  $i$ . Hence, the sensitivity coefficient of the electromagnetic force can be defined as

$$c = \frac{\partial F_e}{\partial (i^2)} \quad (4)$$

Equation 4 reflects sensitivity of the electromagnetic force versus the current square, which denotes the required specific amount of the current square for some kinds of electromagnetic mechanisms as to produce electromagnetic force. For the electromagnet,

$c = \frac{\partial F_e}{\partial(i^2)} = \frac{N^2 \mu_0 S}{2\delta^2}$ , which coefficient is inversely proportional to the square of motion displacement  $\delta$ . For the discoid repulsion mechanism and the solenoid type thrust mechanism, the sensitivity coefficient is  $c = \frac{\partial F_e}{\partial(i^2)} = \frac{dM}{dx}$ , and which mainly depends on the derivative of the mutual inductance to the stroke displacement.

Given the electromagnetic force formula, when the moving part of the electromagnet travels to the last stage of the trip length, where  $\delta$  is close to zero, then the sensitivity coefficient will tend to be infinite and the mechanism becomes uncontrollable, which means small current change may cause infinite change of the electromagnetic force. Even though with impact of the core saturation, where at the last stage of the trip the magnetic induction is approximately constant, the electromagnetic force still becomes uncontrollable. Therefore, the sensitivity coefficient can reflect both the structural parameters interactions and also the dynamic characteristics and controllability of the electromagnetic system. In fact, the moving process of the electromagnet can be analyzed from the perspective of control theory, as is shown in Figure 1.

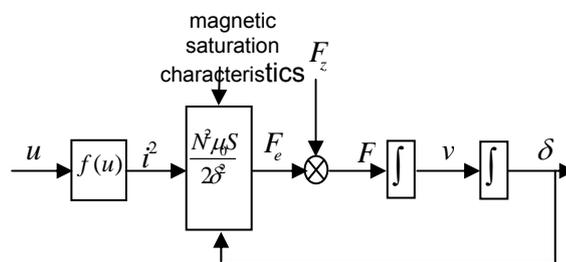


Figure1. Schematic Diagram of the Electromagnet Transmission System

In Figure 1,  $u$  is the supply voltage,  $i$  is the coil current,  $f(u)$  is the function to describe the relationship between the mechanism current and voltage,  $F_z$  is the counterforce,  $F_e$  is the electromagnetic force,  $F$  is the aggregate force applied to the movable part,  $v$  is the velocity and  $\delta$  is the stroke displacement.

It can be seen from Figure 1, increase of the electromagnetic force  $F_e$  will lead to increase of the aggregate force  $F$ , which results in decrease of the stroke  $\delta$ . As a result, this decrease will again lead to increase of the electromagnetic force  $F_e = i^2 \frac{N^2 \mu_0 S}{2\delta^2}$ , eventually causing the aggregate force  $F$  to increase. Hence, without considering the saturation aspect, the electromagnet mechanism essentially constitutes a positive feedback system, which will eventually lead to a uncontrollable motion process. The sensitivity coefficient  $c_1 = \frac{N^2 \mu_0 S}{2\delta^2}$  is inversely proportional to the square of the stroke displacement, which is the main cause to make the mechanism a positive feedback system.

On the other hand, if an electromagnetic mechanism is a negative feedback system versus the stroke displacement, which means an increase of the electromagnetic force  $F_e$  will eventually lead to a decrease of the aggregate force. However, the sensitivity coefficient will be very small if the stroke  $\delta$  is very small, which still makes the system uncontrollable.

Therefore, rational design of the electromagnetic mechanisms neither causing themselves a positive nor a negative feedback system, namely, the electromagnetic force sensitivity coefficient changes little within the stroke range and with a large value, will be the

prerequisite to make the electromagnetic mechanisms a controllable system. But for the discoid repulsion mechanism and the solenoid type thrust mechanism, the controllability depends mainly on the derivative change  $\frac{dM}{dx}$  of the fixed and the moving coils. Regarding the motion

process shown in Figure 2, changes of the sensitivity coefficient  $c$  of the solenoid type thrust mechanism are given in Figures 3 and 4 within a certain range of the electromagnetic force, in the case of 15 discoid turns and with the same resistance. It can be seen from the Figures, when the discoid repulsion mechanism is within the range of 1mm to 33mm, the sensitivity coefficient falls in the scope of  $1 \times 10^{-4}$  to  $4.6 \times 10^{-4}$ , which changes greatly with a large value. If the solenoid type thrust mechanism is within the range of 1mm to 22mm, the sensitivity coefficient will be from  $1 \times 10^{-4}$  to  $1.7 \times 10^{-4}$ , which changes little and with a very small value, only about one-third of the discoid repulsion mechanism

In the above simulation, the diameter of the center hole of the discoid repulsion mechanism is 15mm, the radius of the solenoid thrust mechanism adopts the maximum radius of the discoid repulsion mechanism, and the ratio of the inner and the outer solenoid radius is close to 1.

Figure 5 shows the changes of the maximum sensitivity coefficient of the electromagnetic force with the increase of the turns of the discoid repulsion mechanism and the solenoid type thrust mechanism. As can be seen from the Figure 5, increase of the turns enables a sensible improvement of the sensitivity coefficient, which means an effective measure to increase the coefficients

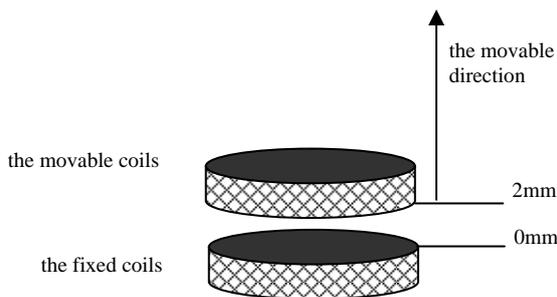


Figure 2. The Discoid Repulsion Motion Diagram

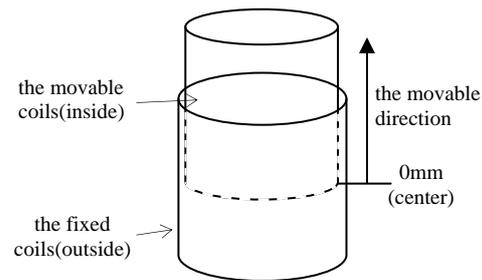


Figure 3. The Solenoid Type Thrust Motion Diagram

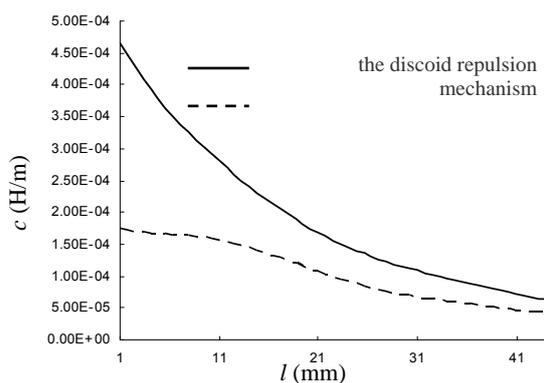


Figure 4. Changes of the Electromagnetic Force Sensitivity Coefficient

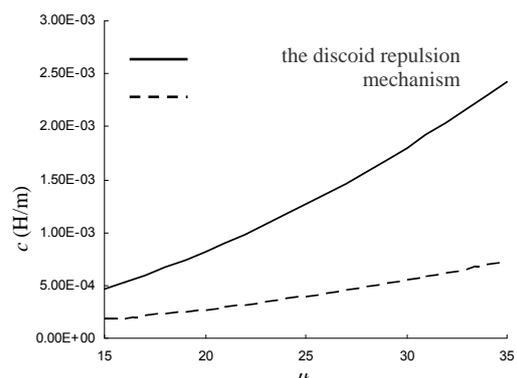


Figure 5. Changes of the Maximum Sensitivity Coefficient

### 3. The Initial Time Constant Index

Before the moving coil of the electromagnetic mechanism starts to move, the whole system can be regarded as a simple RLC discharge circuit. In order to ensure the discharge

produces sufficient energy and to make the capacitor voltage drop slightly after action, generally a large capacitance  $C$  and a small loop inductance are chosen. Hence, the loop system can approximately be treated as a first-order circuit, i.e. a RL circuit. As shown in Figure 6, the current can be approximately expressed by Equation 5, where  $U$  is the supply voltage,  $R_{\Sigma}$  is the total resistance of two coils,  $L_{\Sigma}$  is the total inductance of two coils. As direction of the motion is in accordance with that shown in Figures 2 and 3, then  $L_{\Sigma}=2L-2M$ , where  $L$  is the inductance of each coil,  $M$  is the mutual inductance between the two coils and  $K$  is the control switch.

$$i = \frac{U}{R_{\Sigma}} \left( 1 - e^{-\frac{R_{\Sigma} t}{L_{\Sigma}}} \right) \quad (5)$$

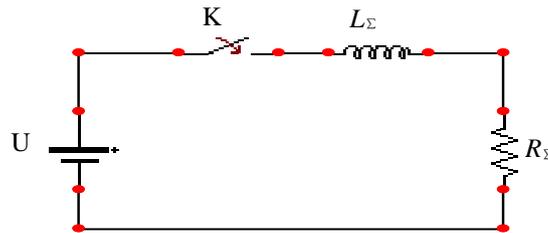


Figure 6. Equivalent Excitation Loop Prior to Action of the Electromagnetic Mechanism

Regarding the electromagnetic mechanism, the time constant is determined by the movable and the fixed coils of the mechanism. This time constant is defined as the initial time constant, namely  $\tau = L_{\Sigma} / R_{\Sigma}$ . The constant determines the excitation time of the mechanism before arriving at the pick-up current required. The greater the time constant is, the longer of the excitation time will be and the less conducive to the realization. Therefore, the optimal design of the mechanisms should pay attention to availability of small initial time constant. Figure 7 shows the initial time constant of the discoid repulsion mechanism and the solenoid type thrust mechanism in term of the same resistance. It can be seen from Figure 7, the initial time constant of the discoid repulsion mechanism is smaller than that of the solenoid type thrust mechanism, which is more conducive to shorten the excitation time.

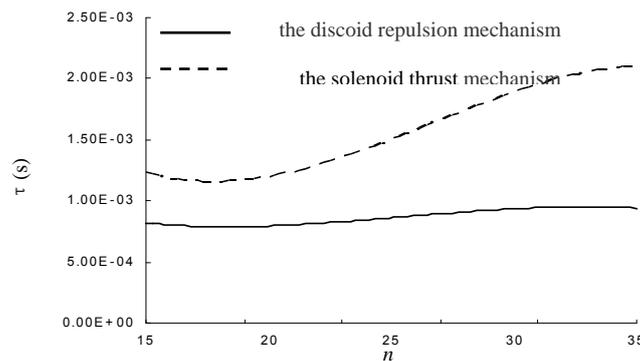


Figure 7. The Initial Time Constant  $\tau$  of the Typical Mechanisms

#### 4. The Sensitivity Contribution Index

A big electromagnetic force sensitivity coefficient normally means a large electromagnetic force to be achieved for a given source current, so this coefficient is one of the pursued goals in the optimal topology design. However, if the coefficient changes due to topology modifications, it is difficult to guarantee whether the response time of the entire system will fulfill the requirement.

In accordance with the electromagnetic force formulas given in Equation 3, the electromagnetic power of the mechanism can be expressed as

$$P = F_e \cdot v = i^2 \cdot \frac{dM}{dx} \cdot v \tag{6}$$

where,  $P$  is the electromagnetic power,  $F_e$  is the electromagnetic force,  $i$  is the coil current and  $v$  is the moving speed.

Similar to the expression of the resistive power,  $\frac{dM}{dx} \cdot v$  in Equation 6 can be regarded as a nonlinear resistor, the time constant of which after mechanism motion is given by

$$\tau = \frac{L_\Sigma}{R_\Sigma + \frac{dM}{dx} \cdot v} = \frac{1}{\frac{R_\Sigma}{L_\Sigma} + \frac{dM/dx}{L_\Sigma} \cdot v} \tag{7}$$

Reorder  $\frac{dM/dx}{L_\Sigma} = k$  in Equation 7, then a sensitivity contribution coefficient can be defined as the ratio between the electromagnetic force sensitivity coefficient  $c$  and the total inductance  $L_\Sigma$ , namely

$$k = \frac{c}{L_\Sigma} \tag{8}$$

Figure 8 shows a comparison of the electromagnetic force sensitivity contribution coefficient of the two mechanisms. Figure 9 gives the maximum value of two mechanisms sensitivity contribution coefficient with coil turns change. As can be seen from the above two Figures, in terms of the movement length or the turns change, the discoid repulsion mechanism is preferable to the solenoid thrust mechanism.

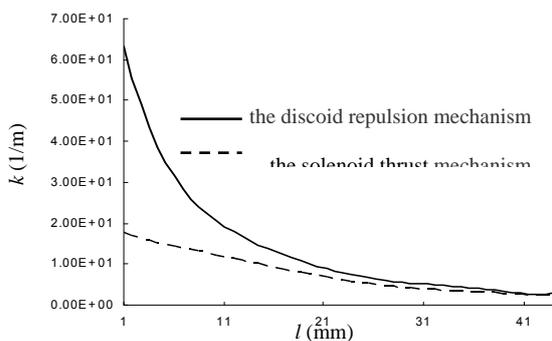


Figure 8. The Electromagnetic Force Sensitivity Contribution Coefficients of the Two Typical Mechanisms

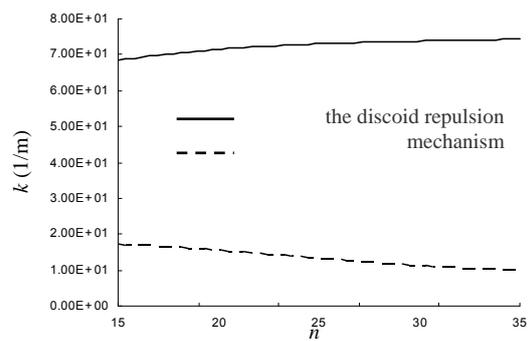
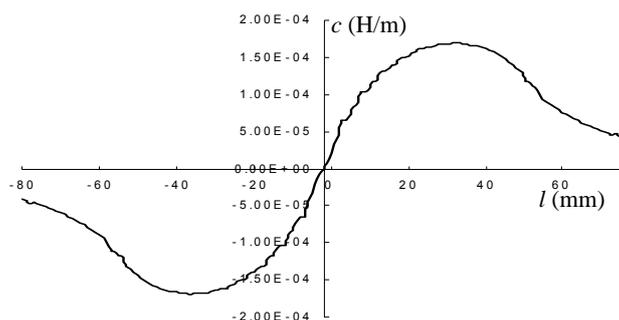


Figure 9. The Maximum Value of the Sensitivity Contribution Coefficients Versus Turns Change

### 5. Conclusion

Based on studies in terms of controllability, response time, moving speed and other aspects of the electromagnetic mechanisms, three interrelated parameters, namely, the sensitivity coefficient, the initial time constant and the sensitivity contribution coefficient, are proposed with corresponding definitions. These specific indexes can basically reflect characteristics of nowadays fast actuator topologies, which facilitate optimization of the topology

design as well as further exploration of novel topologies of good performance. With proper comparison of the three specific parameters regarding various mechanisms, the discoid repulsion mechanism is found with better performance than the solenoid type thrust mechanism. However, in term of the sensitivity coefficient, the solenoid type thrust mechanism possesses recovery characteristics while the discoid repulsion mechanism does not, as shown in Figure 10, which will help reduce the travel speed at the last stage of the actuator, thereby reducing the collision bounce of the mechanism. In another word, multiple aspects should be comprehensively considered for optimal topology design of the actuators, however, the proposed three specific parameters in this paper presents feasible route to quantitative evaluation of different types of mechanisms.



## References

- [1] Yukimori K, Kenichi K, Hiroyuki S, et. al. *Development of the high speed switch and its application*. Conference Record of IAS Annual Meeting (IEEE Industry Applications Society). 1998; 3: 2321-2328.
- [2] Tao He. Safety Analysis and Design for the Switch Control Unit of All-electronic Computer Interlocking System, repulsion mechanism. *TELKOMNIKA Indonesia Journal of Electrical Engineering*. 2012; 10(5): 1057~1061.
- [3] Steurer M, Brechna H, Frohlich K. A nitrogen gas cooled, hybrid, high temperature superconducting fault current limiter. *IEEE Trans. on Applied Superconductivity*. 2000; 10(1): 840-844.
- [4] Chen Gang, Jiang Daozhuo, Cai Yonghua, et al. *Study on a novel solid state fault current limiter with bypass reactor*. Proceedings of the CSEE. 2004; 24(7): 200-205.
- [5] Mokhtari H, Dewan SB, Iravani MR. Analysis of a static transfer switch with respect to transfer time. *IEEE Transactions on Power Delivery*. 2002; 17(1): 190-199.
- [6] Zhu Pengcheng, Li Xun, Kang Yong, et al. *Study of control strategy for a unified power quality conditioner*. Proceedings of the CSEE. 2004; 24(8): 68-73.
- [7] Yang Han. A Pedagogical Approach for Modeling and Simulation of Switching Mode DC-DC Converters for Power Electronics Course. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2012; 10(6): 1319~1326.
- [8] Li Qingmin, Liu Weidong, Qian Jiali, et al. An analytical method for electromagnetic repulsion mechanism. *Transactions of China Electrotechnical Society*. 2004; 19(2): 20-40.
- [9] Lou Jie, Li Qing-min, Sun Qing-sen, et al. *Dynamic characteristics simulation and optimal design of the fast electromagnetic repulsion mechanism*. Proceedings of the CSEE. 2005; 25(16): 23-29.
- [10] LOU Jie, LI Qingmin, LIU Hongshun, et al. Theoretical and experimental research on a novel actuator-oriented electromagnetic mechanism. *Electric Power Applications, IET*. 2011; 5(6): 524-520.