A Study on an Effect of the Flux feedback on an Open-loop Characteristic of the Magnetic Levitation System

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Abstract

This paper deals with an open-loop characteristic of a magnetically levitated system including flux feedback. In order to design a controller to obtain a good disturbance rejection and to be insensitive to parameter variations, it might be useful to employ a flux feedback loop. The air gap flux which can be sensed by a proper sensor has linear relationship with respect to the change of the current and the air gap. This linear property decreases the inherent nonlinearity of the magnetic suspension system that is caused by the coupling between the electrical actuator and the mechanical plant. Simulation results show that the flux feedback loop makes an improvement of the performance of the magnetic suspension system against the load variations.

1 Introduction

In recent trends to develop various technologies the word "contactless" has been begun to receive notable attention because of its effectiveness and maintenance free properties that is not possible to achieve in the conventional "contact" system. The typical representative contactless system is a magnetic suspension system which is commonly known as Magnetically Levitated system (*Maglev*). The first trial for the *maglev* has been performed at the University of Virginia in 1937 which has been intended to test magnetic bearing systems.

Recently there are various applications employing the magnetic levitation configuration as a core technology, such as the magnetically levitated train system, the high speed turbo compressors, the flywheel energy storage system, and the artificial heart pump.

The magnetically levitated system can be divided into two parts based on the levitation method: one is a repulsive type using super conductors. One of disadvantages of this type of suspension system is that it is needed to operate below the critical speed when the suspended object is stationary because an active suspension actuator and a controller are not included which make it possible to pass through the critical speeds. The other type is electromagnetic suspension system (EMS) using ferromagnetic or permanent magnet. The EMS type has one significant advantage in that it provides attraction force at zero speed, but such system is inherently unstable. In order to overcome the inherent instability an active controller plays a very important role in the electromagnet type suspension system to make the stable suspension and to maintain the suspended object within the nominal air gap.
Especially, when external disturbance or parameter variations affect on the active controller of the *Maglev,* the system may cause a malfunction of the suspension system. In such case a controller that has a robustness property should be introduced, or a system model should be considered to avoid the effects of the external disturbance or parameter variations.

In many papers and literatures the design methodologies of the active magnetic suspension controllers have already been presented. However the papers for the analysis of the open-loop characteristics of the magnetic suspension system have rarely presented. It is sometimes very valuable to make a focus on the inherent properties of the magnetic suspension system to achieve a design of the improved active controller against the system parameter variations. The purpose of this paper is to show the effectiveness of the flux feedback loop of the air gap in the open loop characteristic of the magnetic suspension system when a constant voltage is applied to the electromagnet coils.

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In this paper we summarize the fundamental mathematical model of the EMS system, which does not include the flux feedback loop and we show a modified mathematical model including the flux feedback loop. In the flux feedback loop the estimated flux is linearly proportional to the magnetic excitation current and inversely proportional to the air gap. Simulation results verify that the magnetic suspension system including flux feedback loop has robustness against the parameter variations. Finally conclusions are summarized.

2 Fundamental Mathematical Model

Fig.1 shows a simple schematic diagram for EMS systems which have the electromagnets as the suspension actuators, linear induction motor and reaction plate for the vehicle propulsion, and four degree of freedom rotational

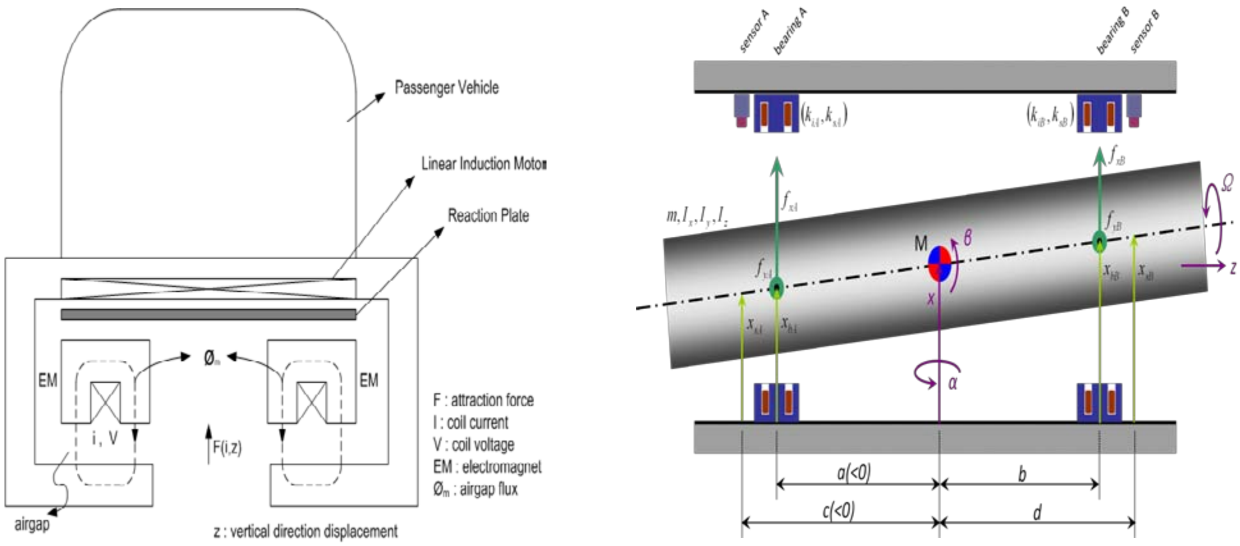

Fig. 1 Schematic diagram for EMS system

rotor that can be applied to the flywheel energy storage system. As we see in Fig. 1 the passenger vehicle and the bogie can be levitated by the electromagnets attraction force. Once the bogie is levitated the propulsion system (linear motor and reaction plate) is activated to move the passenger vehicle. For the rotational rotor, left and right electromagnetic bearings support the rotor to make levitation so that the rotor can rotate without any contact with the stator. For the simplification of the mathematical model of the suspension system shown in Fig. 1 we modify Fig. 1 to Fig. 2

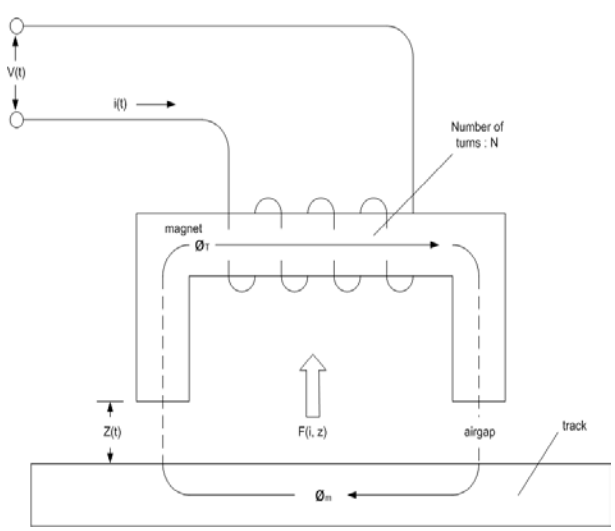

Fig. 2 Simplified schematic diagram

The mathematical model of this system is divided into two parts: One is the plant (mechanical) dynamics and the other is the actuator dynamics. The plant (mechanical) dynamics is

$$m\ddot{z} = F(i,z) - mg - f_d \tag{1}$$

where m is the total mass of the controlled object, g is the gravitational acceleration, f_d is the external disturbance force acting on the controlled object. In Eqn. (1) $F(i,z)$ is the electromagnets attraction force which is proportional to the current deviation and inversely proportional to the air gap deviation, expressed such as:

$$F(i,z) = \frac{B^2 A}{\mu_0} = \frac{\mu_0 N^2 A}{4}\left(\frac{i(t)}{z(t)}\right)^2 \tag{2}$$

where B is the flux density of the magnetic core material, A is the cross sectional area of the pole face of the electromagnet, μ_0 is the permeability in the air space, N is the number of turns. In order to drive Eqn. (2) it is necessary to check the relation between the inductance and the magnetic flux density.

$$L(i,z) = \frac{N}{i}\Phi_m = \frac{N}{i(t)}\frac{Ni(t)}{R_T} \tag{3}$$

where $R_t = \frac{2z(t)}{\mu_0 A} = \frac{V_T}{\phi_m}$ is the reluctance of the magnetic circuit. V_T is the electromotive force. Normally the reluctance in the magnetic core is assumed to be negligible compared with the air gap, thus the coil inductance becomes

$$L(i,z) = \frac{\mu_0 N^2 A}{2z(t)} \tag{4}$$

$Li(t) = NBA$ and Eqn. (4) yield the magnetic flux density such as:

$$B = \frac{Li(t)}{NA} = \frac{N^2 \mu_0 A i(t)}{2z(t)NA} = \frac{\mu_0 N i(t)}{2z(t)} \tag{5}$$

Substituting Eqn. (5) into $F(i,z) = \frac{B^2 A}{\mu_0}$ yields Eqn. (2). Eqn. (2) has high nonlinearity and it is not easy to use Eqn. (2) without doing the linear approximation with respect to the nominal point, (i_0, z_0) For the linear approximation the Taylor Series Expansion is usually employed. From the Taylor Series Expansion the Eqn. (2) becomes

$$F(i,z) = k_i i(t) - k_z z(t) \tag{6}$$

where $k_z = \frac{\mu_0 N^2 A i_0^2}{2z_0^3}$, $k_i = \frac{\mu_0 N^2 A i_0}{2z_0^2}$, are the coefficients for the linear approximation of Eqn. (2).

In Eqn. (6) the stiffness k_z has negative sign which means that once the attractive force of the electromagnets is activated the controlled object is attracted until the electromagnets stop attracting the controlled object. This is one of the reasons why the electromagnet suspension system should has the active controller to control the air gap deviation.
The actuator dynamics is

$$v(t) = Ri(t) + \frac{d}{dt}\left[L(i,z)i(t)\right] \\ = Ri(t) + \frac{\mu_0 N^2 A}{2z(t)}\frac{d}{dt}i(t) - \frac{\mu_0 N^2 A i_0}{2z(t)^2}\frac{d}{dt}z(t) \tag{7}$$

where v is the coil voltage, R is the coil resistance, L(i, z) is the coil inductance which is the function of the air gap displacement. It should be noted that there is a variation of the inductance with respect to the air gap displacement in the second term, and that the third term denotes a voltage which varies with changes in the air gap z(t) and its rate of change similar to back EMF voltage. By using equations (1), (6), (7) we can drive a state space equation such as:

$$\begin{bmatrix} \dot{z} \\ \ddot{z} \\ \dot{i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{-k_z}{m} & 0 & \frac{k_i}{m} \\ 0 & \frac{k_z}{k_i} & \frac{-R}{L} \end{bmatrix} \begin{bmatrix} z \\ \dot{z} \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} v + \begin{bmatrix} 0 \\ \frac{1}{m} \\ 0 \end{bmatrix} f_d \tag{8}$$

Fig. 3 shows the simple block diagram for the open-loop EMS system which does not include the flux feedback signal. The transfer function of the open loop system is induced by the Laplace transform of Eqn. (8) for each state variables, which is

$$z(s) = \left[\frac{\left(\frac{k_i}{mR}\right)}{\left(1+\frac{L}{R}s\right)\left\{s^2 + \frac{k_i^2}{mR\left(1+\frac{L}{R}s\right)}s - \frac{k_z}{m}\right\}} \right] v(s) \tag{9}$$

with $f_0 = 0$. As we see in Eqn. (9) the negative stiffness k_z makes the system unstable, which means one of the poles of the characteristic equation exists in the right half plane of the

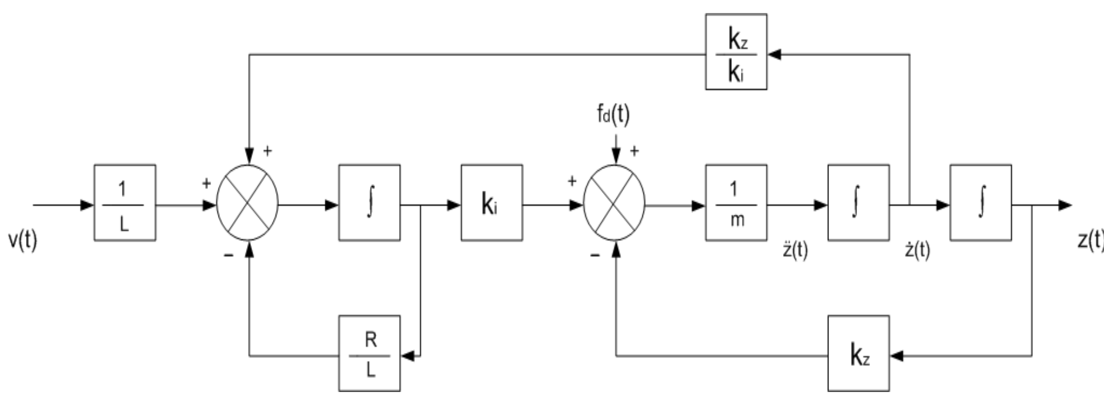

Fig. 3 Open-loop diagram without flux

3 Flux Feedback Loop

In this section we show an approach using flux feedback to estimate open loop characteristics. The flux which is produced by the core magnet is proportional to the pole face area as:

$$\begin{aligned}\Phi &= BA \\ &= \frac{\mu_0 NAi}{2z} = k_{\Phi}\frac{i}{z}\end{aligned} \tag{10}$$

If the magnetic flux ∅ is fed back to the amplifier that activates the electromagnets the terms for the dynamics of the electromagnet actuators should be modified so that the force component which is included in the magnetic flux should be included in the actuator dynamic equation. This yields equation (11)

$$\begin{aligned}v(t) &= Ri(t) + N\frac{d\Phi}{dt} \\ &= Ri(t) + \frac{\mu_0 N^2 A}{2z_0}\Delta i(t) - \frac{\mu_0 N^2 A i(t)}{2z_0^2}\Delta z(t)\end{aligned} \tag{11}$$

where $k_{fi} = \frac{\mu_0 AN^2}{2z_0}$, $k_{fz} = \frac{\mu_0 AN^2 i_0}{2z_0^2}$

Substituting $v(t) = v_0 + \Delta v(t)$, $i(t) = i_0 + \Delta i(t)$in Eqn. (11) yields

$$\begin{aligned}\Delta v(t) &= R\Delta i(t) + L_0\Delta\dot{i} - k_i\Delta\dot{z} \\ &\quad - k_{\phi\phi}(k_{fi}\Delta i(t) - k_{fz}\Delta z(t)) \\ &= R\Delta i(t) + L_0\Delta\dot{i} - k_i\Delta\dot{z} - k_{\phi\phi}\Phi\end{aligned} \tag{12}$$

Compare to the Eqn. (7) the flux feedback term is included in Eqn. (12) which is expressed as linear combination of the coil current and air gap deviation. A combination of the three equations (1), (6), (12) induces the state space model including the flux feedback such as:

$$\begin{bmatrix}\dot{z} \\ \ddot{z} \\ \dot{i}\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{-k_z}{m} & 0 & \frac{k_i}{m} \\ \frac{k_{\Phi\Phi}k_{fz}}{L} & \frac{k_z}{k_i} & \frac{(-R-k_{\Phi\Phi}k_{fi})}{L}\end{bmatrix}\begin{bmatrix} z \\ \dot{z} \\ i\end{bmatrix} + \begin{bmatrix}0 \\ 0 \\ \frac{1}{L}\end{bmatrix}v + \begin{bmatrix}0 \\ \frac{1}{m} \\ 0\end{bmatrix}f_d \tag{13}$$

Fig. 4 presents the open-loop diagram with flux feedback loop. In this figure$k_{\emptyset\emptyset}$ represents the flux feedback gain which includes the EMS force component.

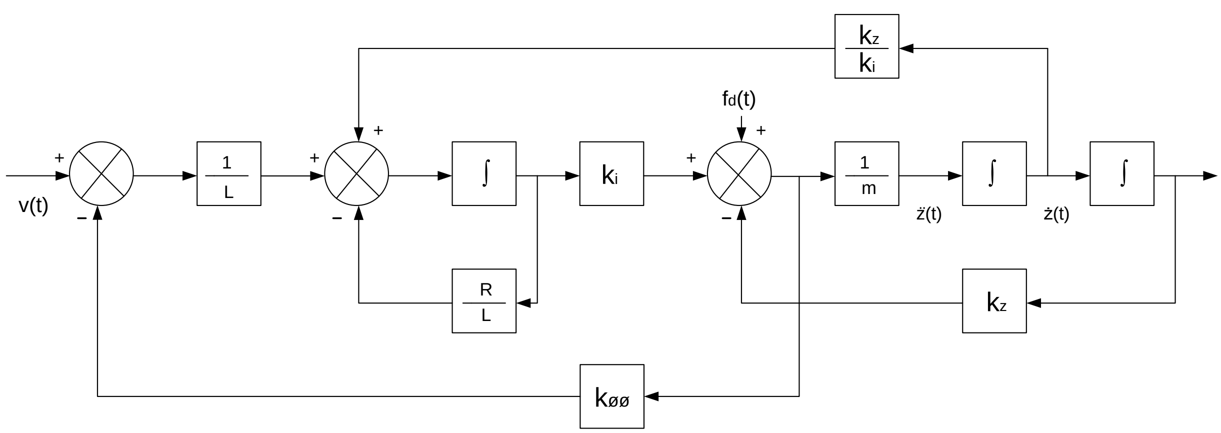

Fig. 4 Open-loop diagram with flux feedback

From the characteristic Eqn. (13) the gain of the flux feedback loop $k_{\emptyset\emptyset}$ can be adjusted such that

$$k_{\emptyset\emptyset} = -\frac{k_z R}{k_i k_{fz} - k_z k_{fi}} \tag{14}$$

The input-output transfer function is reduced to

$$z(s) = \frac{\frac{k_i}{m}L}{s^2\left(s + \frac{R}{L} + \frac{k_{\Phi\Phi}k_{fi}}{L}\right)} v(s) \tag{15}$$

which indicates that flux feedback makes the system conditionally stable

4 Simulations

For the simulations to estimate the open-loop properties of the electromagnet suspension system we set the following parameters shown in Table 1. In the simulations to assess the effectiveness of the flux feed loop we made the load variations in mass. Fig. 5 and Fig. 6 show the air gap deviation for the case of when the load acting on the controlled object is changed. When the load is 100[Kg] (Fig. 5) without the flux feedback loop the controlled object contacts (dashed line) the electromagnets at time 50[sec]. In case of 500[Kg] (Fig. 6) it takes more time to contact the electromagnet than that of Fig. 5, however we see that the vibration amplitude becomes bigger and bigger with time. This is because of the inherent unstable characteristics of the magnetic suspension system.
On the contrary, the simulation results with flux feedback loop shown in Fig. 7 and Fig. 8 present very good characteristics against the load variation. Fig. 7 is for the case when the load is 100[Kg]. In this figure we see very good robustness when there is a parameter variation of the EMS system. The small vibration in Fig. 7 is because there is no feedback active controller. Thus any kind of feedback controller can eliminate this vibration. In Fig. 8 we see slower vibration and bigger amplitude than that of Fig. 7. This is because of the much heavier load (500[Kg]).

Table 1. Parameters for EMS system

Variables	Value	Unit
Mass : m	100, 500	[Kg]
Coil Inductance : L	72	[mH]
Coil Resistance : R	0.7	[Ω]
Steady Current : i_0	1	[A]
Cross Sectional Area : A	2.2×10^{-6}	[m^2]
Number of turns : N	140	[turns]
Permeability : μ_0	$4\pi\times10^{-7}$	[H/m]

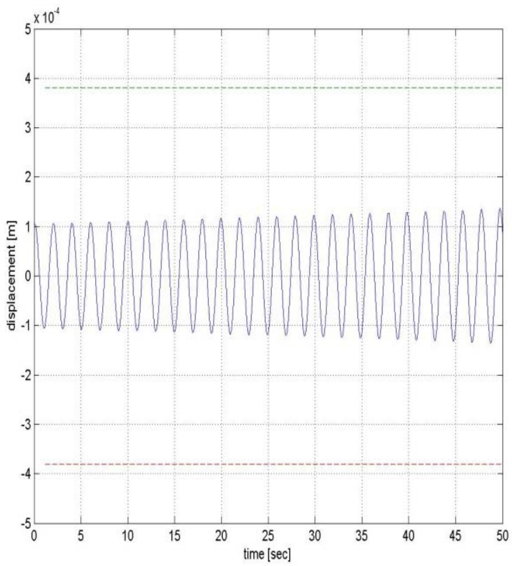

Fig. 5 Gap deviation without flux feedback (m=100[Kg])

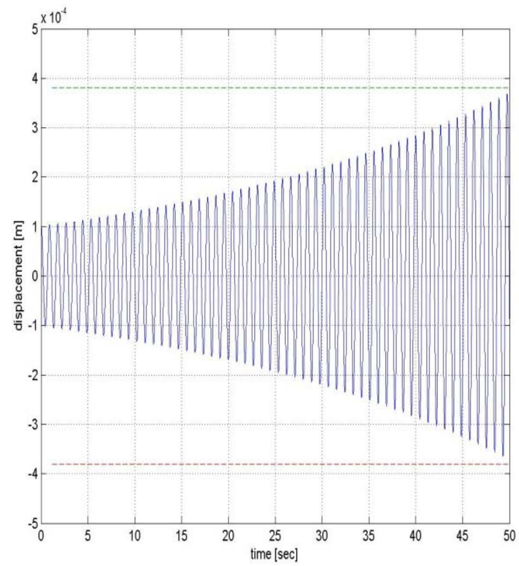

Fig. 6 Gap deviation without flux feedback (m=500[Kg])

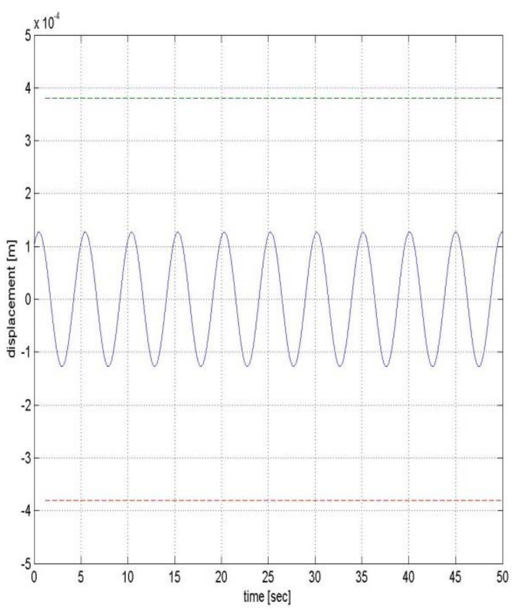

Fig. 7 Gap deviation with flux feedback (m=100[Kg])

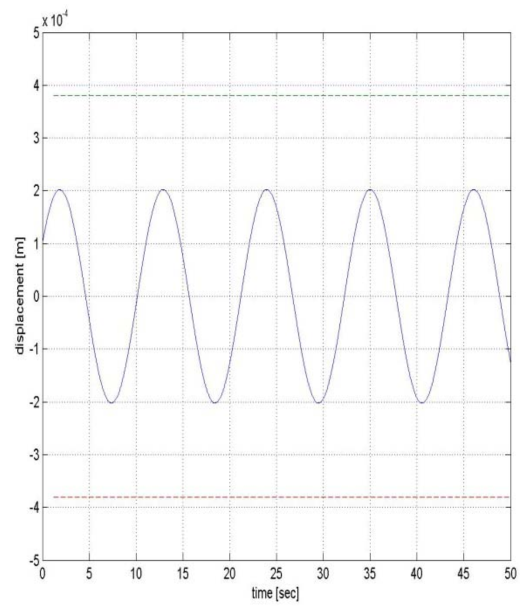

Fig. 8 Gap deviation with flux feedback (m=500[Kg])

5 Conclusions

In this paper we have dealt with the open loop characteristics of the electromagnets suspension system which has the flux feedback loop. The flux feedback loop increases the system robustness against the parameter variations even if no active controller is employed. This property comes from the linear combination of the air gap displacement and the coil current which is different from the conventional open loop structure. First, we showed the fundamental mathematical model which has no flux feedback loop, and then introduced the modified mathematical model including the flux feedback loop. Finally we achieved the robustness against the parameter variations of the modified open loop scheme by the simulations. This modified open loop scheme can be applied to a system which has a frequent load variation such as magnetically levitated train system.

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