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Runout Control of a Magnetically Suspended High Speed Spindle Using Adaptive Feedforward Method

Seung-Kook. Ro[1,#], Jin-Ho Kyung[1], Jong-Kwon Park[1]

[1] Intelligence and Precision Machine Department, Korea Institute of Machinery and Materials

ABSTRACT

In this paper, the feedforward control with least mean square (LMS) adaptive algorithm is proposed and examined to reduce rotating error by runout of an active magnetic bearing system. Using eddy-current type gap sensors for control, the electrical runout caused by non-uniform material properties of sensor target produces rotational error amplified in feedback control loop, so this runout should be eliminated to increase rotating accuracy. The adaptive feedforward controller is designed and examined its tracking performances and stability numerically with established frequency response function. The designed feedforward controller was applied to a grinding spindle system which is manufactured with a 5.5 kW internal motor and 5-axis active magnetic bearing system including 5 eddy current gap sensors which have approximately 15 ~ 30 μm of electrical runout. According to the experimental results, the error signal in radial bearings is reduced to less than 5 μm when it is rotating up to 50,000 rpm due to applying the feedforward control for first order harmonic frequency, and corresponding vibration of the spindle is also removed.

Key Words : magnetic bearing system, electrical runout, runout control, adaptive feedforward control, LMS algorithm, IIR notch filter

1. Introduction

Magnetic bearing systems are very advantageous for applications of high-speed rotating machines due to lack of mechanical contact between rotors and stators. So far, magnetic bearings are applied in many industries with high speed and extreme environment including machine tool spindles.[1] The rotational error of magnetic bearing system is critical for machine tools applications because it is directly related with machining error. There are some sources occurring rotational error in magnetic bearings, for example, unbalance of rotor mass, external excitation such as cutting force, modeling error from nonlinearity and electrical / mechanical runout of sensor target, and also many control techniques are researched to minimize these errors.[2,3]

In case of using eddy current sensor, the electric runout due to non-uniform material properties is more than tens of micron, and not easy to suppress only with feedback controllers. This runout signal during rotation is the sum of harmonic waves of rotating frequency. Only with conventional feedback controller like PID, the harmonic force to suppress this runout generates actual displacement of the spindle and vibration.

The notch filters and feedforward filters substituting harmonic signal are good solutions to reject harmonic disturbances. But, the notch filter is not applicable for all rotating speed range because the phase lags in the notch filter can weaken stability of the system. For the feedforward method subtracting known harmonic signals, the system stability is not affected, but the runout rejection performances are not guaranteed when system parameters are changing, such as change of frequency and phase of the runout. Therefore, adaptive algorithm is necessary for using feedforward filter in various operating condition.

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Corresponding Author: Seung-Kook Ro
Email: cniz@kimm.re.kr
Tel: +82-42-868-7115, Fax: +82-42-868-7180

In this paper, a feedforward controller with LMS algorithm is proposed to reduce electrical runout effect in a grinding spindle system suspended by magnetic bearing system with digital PID controllers. The designed LMS controller is examined its runout compensation performance with numerical simulation, and convergence coefficient is designed to guarantee the stability of LMS filter in all operating speed range. This controller is applied to a grinding spindle with 5-axis active magnetic bearing for eliminating effect of first order synchronous electrical runout of front and rear radial sensor targets. The experimental result of rotating up to 50,000 rpm shows that the feedforward controller with LMS filter eliminated electrical runout in the command error and reduces rotational error and vibration effectively.

2. Spindle system with Magnetic Bearing

2.1 Internal grinding spindle with active magnetic bearings

A magnetically suspended high-speed internal grinding spindle system is shown in Fig. 1.[1] It has built-in motor with 5.5 kW power, maximum 50,000rpm speed in the middle and two 8-ploe hetero-polar type radial magnetic bearings and an axial magnetic bearing. The five eddy-current gap sensors with resolution 0.1 ㎛ and 80kHz of bandwidth are assembled for sensing 5-axis position of the rotor, and a key phaser is attached for detecting angular position of rotation. The designed specifications of radial magnetic bearings are listed in Table 1.

A digital control system with processor board using TMS320C40 DSP processor, 16-bit A/D and 12-bit D/A is used to control the magnetic bearing system, and the PWM power amplifiers are used to drive coils in electromagnets.

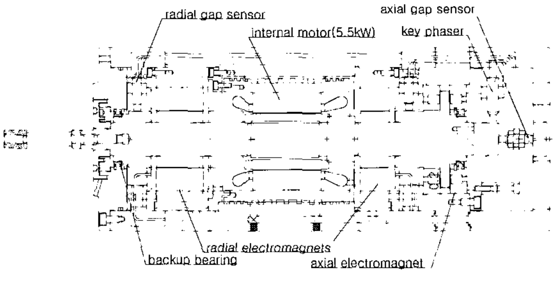


Fig. 1 schematic diagram of the grinding spindle

Table 1 the specifications of radial magnetic bearings

Item	Front Bearing	Rear Bearing
air gap, g_0 [mm]	0.3	0.3
area of a pole, A_p [mm^2]	300	200
number of turn, N [times]	110	110
bias current(bias flux=0.75[T]), I_0 [A]	2.1	2.1
current gain, K_{ix} [N/A]	273	182
position gain, K_x [N/m]	1.77×10^6	1.18×10^6

2.2 Control system of active magnetic bearing

The block diagram of typical 1 axis active magnetic bearing system including feedback controller and feedforward controller to compensate external disturbances is shown in Fig. 2.

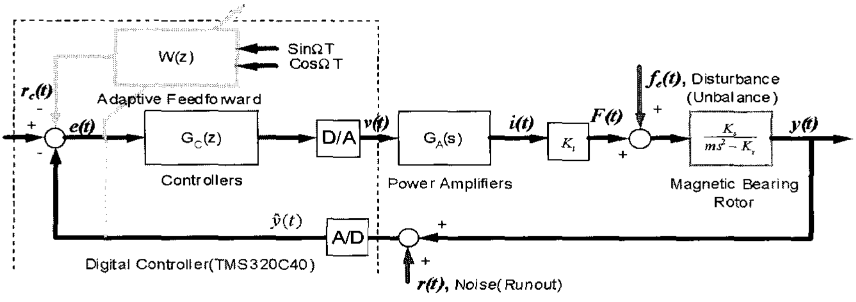


Fig. 2 block diagram of magnetic bearing system with feedforward controller

The sampling frequency of digital control system is 10 kHz, and the dynamic properties of the spindle are as follows, mass M=4.38 kg, moment of inertia J_p= 0.0014 kgm^2, J_t = 0.0362 kgm^2. As its first bending mode frequency, 1.167 kHz is higher than maximum rotating speed, 50,000 rpm, this spindle could be regarded as a rigid rotor and controlled de-centralized 5-axis (front X, front Y, rear X, rear Y and axial direction) separately (direct feedback controller).

From dynamic equation of electromagnet and rotor, the transfer function of magnetic bearing and rotor, $G_R(s)$ was modeled as a 2nd order system (1).

$$G_R(s) = \frac{K_i K_s}{ms^2 - K_x} \tag{1}$$

For front bearing, the equivalent mass m=1.5 kg, and the sensitivity of displacement sensor K_s = 10000 V/m

The power amplifiers were modeled as damped 2nd order function (2), and the measured parameters were K_{amp}=0.8, ζ =1.7 and ω_{np}=2500 Hz for rear bearing, and, because of larger inductance, natural frequency ω_{np} was modeled as 1800 Hz for font bearing.

$$G_A(s) = \frac{\omega_{np}{}^2 K_{amp}}{s^2 + 2\zeta_p \omega_{np} s + \omega_{np^2}} \tag{2}$$

The feedback controller, $G_c(z)$ was chosen a digital PID controller as (3) with proportional gain P=1.6, derivative gain D=0.002, integral gain I=1, N_d=15 and sampling time h=100μ sec.

$$G_c(z) = P + D\frac{N_d(h-1)}{hN_d z + (h-1)} + I\frac{h(z+1)}{2(z-1)} \tag{3}$$

2.3 Runout rejection problem

In most case, the disturbances acting on magnetic bearing spindle system in Fig.2 can be represented as unbalance force $f_e(t)$ on input and noise or runout $r(t)$ on output. If only runout is considered, the actual displacement of rotor, y is described as equation (4).

$$y = \frac{G_R G_C G_A}{1 + G_R G_C G_A}[y_r + r - r_c] \tag{4}$$

The runout $r(t)$ could be described as sum of sinusoidal signals with multiples of rotating frequency.

$$r(t) = \sum R_k \sin(k\Omega t + \phi_k) \tag{5}$$

To minimize rotor displacement by runout $r(t)$, the feedforward compensation signal $r_c(t)$ should be close to runout signal.

3. Design of Runout Control Algorithm

3.1 Feedforward adaptive control with LMS algorithm

The LMS (lease mean square) algorithm is a method to estimate parameters of modeled system in real-time using error object function $V(\theta ,t)$ as described in (6).[4]

$$V(\theta,t) = \frac{1}{2}\left[\xi(t) - \varphi^T(t)\theta(t)\right]^2 \tag{6}$$

The estimated value of a parameter, $\hat{\theta}(t)$ is shown as bellows with estimated value of prior step, $\hat{\theta}(t-1)$ and convergence coefficient μ .

$$\hat{\theta}(t) = \hat{\theta}(t-1) + \mu\varphi(t)\left[\xi(t) - \varphi^T(t)\hat{\theta}(t-1)\right] \tag{7}$$

Therefore if the any error objective function is possible to express as equation (6), it is possible to apply LMS algorithm through equation (7). For runout rejection, the command error $e(t)$ must be minimized, so the objective error function V is expressed as (8).

$$V = e^2(t) = [\hat{y}(t) + \sum(w_{k0}\sin k\Omega t + w_{k1}\cos k\Omega t)]^2 \tag{8}$$

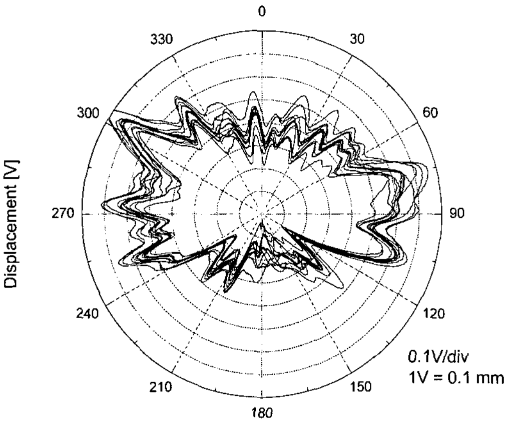
Hence, from (7), the estimation rule is rewritten as bellow.

$$\begin{pmatrix} w_{k0}(t) \\ w_{k1}(t) \end{pmatrix} = \begin{pmatrix} w_{k0}(t-1) \\ w_{k1}(t-1) \end{pmatrix} + \mu e(t)\begin{pmatrix} \sin k\Omega t \\ \cos k\Omega t \end{pmatrix} \tag{9}$$

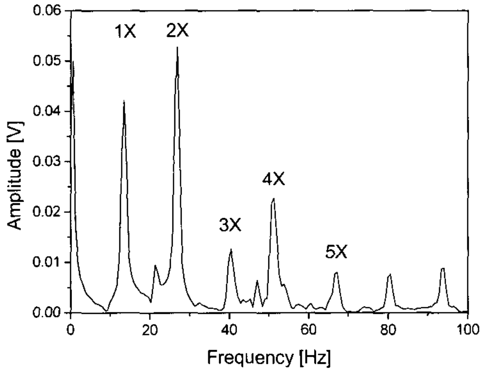
Finally, the Feedforward compensation signal r_c(t) can be achieved as (10).

$$r_c(t) = \sum[w_{k0}(t-1)\sin k\Omega t + w_{k1}(t-1)\cos k\Omega t)] \tag{10}$$

Therefore, by tracking command error signal *e(t)*, the *e(t)* is minimized by feedforward compensation with LMS algorithm, so displacement by runout is reduced. The more number of harmonic multiplier k is used for runout signal estimation, the closer estimation of runout can be get.



(a) measured runout at 800 RPM



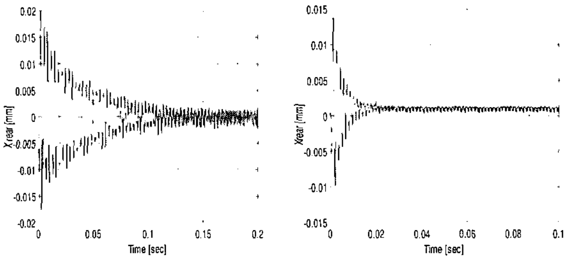
(b) frequency spectrum of the runout signal

Fig. 3 example of measured runout of rear sensor target

3.2 Numerical simulation of runout rejection

The runout rejection performance of the proposed feedforward controller was examined by numerical analysis with 4-dof model of active magnetic bearing rotor system (MATLAB was used). Fig.3 shows an example of runout measured in slow rotation (800 rpm).[7] This electrical runout is about 80 ㎛ in magnitude and has mostly 1X and 2X of rotating speed frequency.

The resultant displacements of rotor with electrical runout measured from actual sensor target during feedforward control for 1X and 2X of rotational frequency (k=1, $2\mu = 0.001$) at 10,000 rpm and 20,000 rpm are shown in Fig.4. In that figure, it was shown that the displacements of rotor were decreased as adaptation went on and converged faster at higher speed.



(a) 10,000 rpm (b) 20,000 rpm

Fig. 4 runout control simulation with LMS algorithm

3.3 Stability analysis of the Feedforward controller

The operating speed of machine tool spindle is not fixed, so it is important to guarantee stability in wide rotational speed for applying feedforward controller. The convergence depends on coefficient μ , which is usually smaller than 0.01. The stability of the designed 4-dof magnetic bearing system with feedforward controller was examined by numerical analysis using transfer function of the feedforward controller.

The transfer function of the feedforward controller with LMS algorithm was derived from Z-transform of equation (9) and (10) at rotational speed $k\Omega$. The following equations are Z-transform of equation (9) and (10) where the $R_c(z)$, $W(z)$ and $E(z)$ are Z-transformed function of $r_c(t)$, $w(t)$ and $e(t)$.

$$\begin{aligned} R_c(z) = &-\frac{1}{2} j\left\{W_{k0}\left(ze^{-jk\Omega}\right) - W_{k0}\left(ze^{jk\Omega}\right)\right\} \\ &+\frac{1}{2}\left\{W_{k1}\left(ze^{-jk\Omega}\right) + W_{k1}\left(ze^{jk\Omega}\right)\right\} \end{aligned} \tag{11}$$

$$W_{k0}(z) = \frac{1}{2}\frac{\mu}{z-1}\left\{-jE\left(ze^{-jk\Omega}\right) + jE\left(ze^{jk\Omega}\right)\right\} \tag{12}$$

$$W_{k1}(z) = \frac{1}{2}\frac{\mu}{z-1}\left\{E\left(ze^{-jk\Omega}\right) + E\left(ze^{jk\Omega}\right)\right\} \tag{13}$$

The transfer function of runrout to command error can be expressed as follows by substituting equations (11) and (12) to (13).

$$R_c(z)=\frac{\mu}{2}\left\{\frac{1}{ze^{-jk\Omega}-1}+\frac{1}{ze^{jk\Omega}-1}\right\}E(z) \tag{14}$$

$$G_{ff}(z)=\frac{R_c(z)}{E(z)}=\mu\frac{\cos k\Omega z^{-1}+z^{-2}}{1-\cos k\Omega z^{-1}+z^{-2}} \tag{15}$$

$$G_n(z)=\frac{E(z)}{R(z)}=\frac{1}{1+G_{ff}(z)}$$
$$=\frac{1-2\cos k\Omega z^{-1}+z^{-2}}{1-(2-\mu)\cos k\Omega z^{-1}+(1-\mu)z^{-2}} \tag{16}$$

From (16), it can be noted that the feedforward controller has same transfer function of IIR notch filter, and the notch bandwidth frequency is narrower with smaller convergence coefficient μ .[5]

Fig. 5 shows the result of numerical stability analysis with respect to rotating speed and convergence coefficient. If any of poles of system including feedforward controller is larger than 1 of its magnitude, this system go unstable and diverge.

According to the result, it was shown that the sign of μ must be changed at 6,000 rpm (100 Hz) to prevent diverging. Therefore, to guarantee stability in all operating range, the convergence coefficient μ was set to -0.001 at low speed under 5,500 rpm, 0 for transition speed range 5,500 to 6,500 rpm, and 0.001 for high speed over 6,500 rpm. In the transition speed range, the μ =0 means there is no tracking in LMS filter, and $w_{k0}(t)$ and $w_{k1}(t)$ are remain constants, but the compensation is still going on according to estimated runout in other speed range.

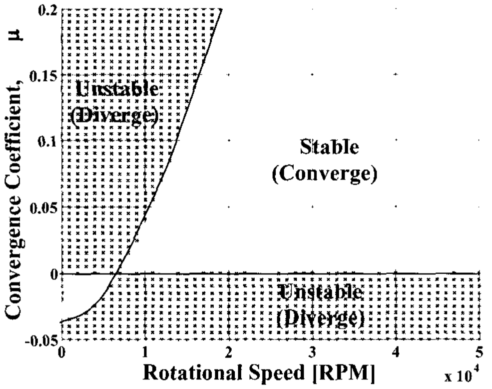
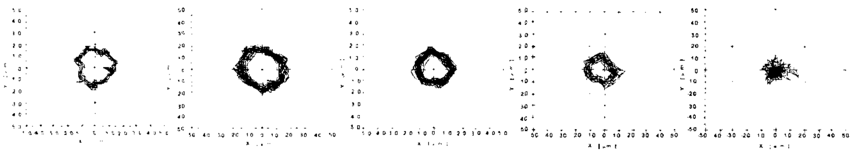


Fig. 5 Stability analysis with Feedforward Control

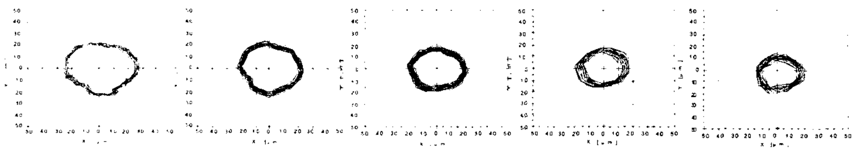
4. Experimental Results

4.1 Rotational response without runout control

Fig. 6 shows X-Y plot of front and rear radial sensor outputs measured during the spindle is running 10,000 ~ 50,000 RPM. The magnitude of the sensor output was about 20 μm peak-to-peak for the front bearing and 30 μm for the rear bearing in 50,000 rpm. Considering these trajectories were almost in circular shape and decreased their size as rotational speed increased, it can be noticed that the electrical runout signals with first order harmonic frequency were dominant in the sensor responses. The command errors *e(t)* of this condition had exactly same magnitude of the sensor signal because there was no compensation by feedforward controller.

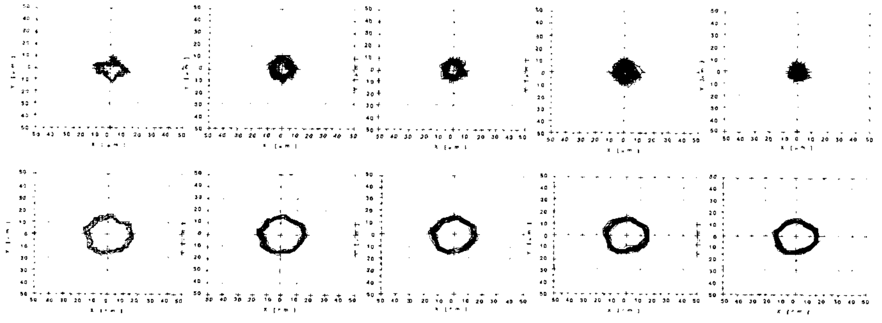


(a). front radial sensor



(b). rear radial sensor

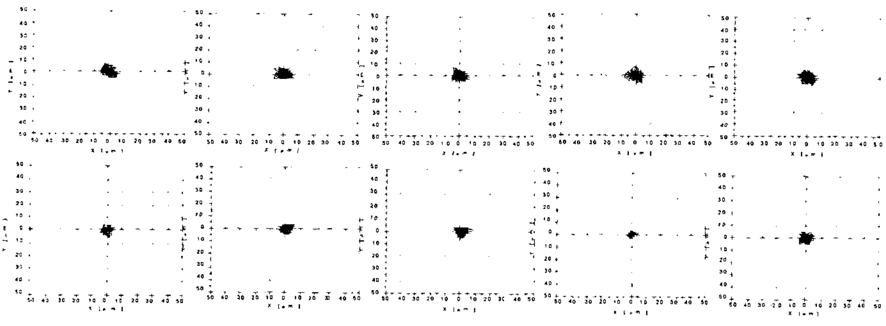
Fig. 6 rotational response at sensors without feedforward control (10,000 ~50,000 rpm, 10 μm/div)



(a) front sensor

(b) rear sensor

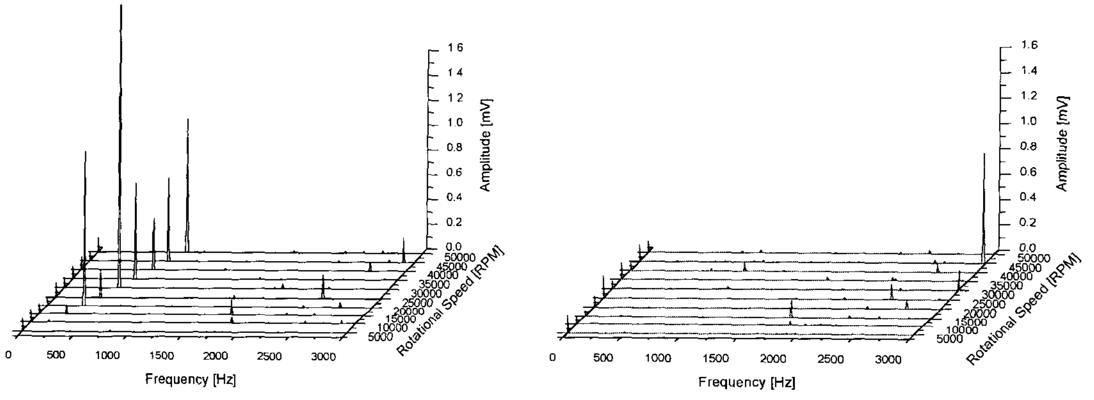
Fig. 7 measured sensor output with feedforward control (10,000~50,000 rpm, 10 ㎛/div)



(a) front error

(b) rear error

Fig. 8 command error with feedforward control (10,000~50,000 rpm, 10 ㎛/div)



(a) no feedforward

(b) with feedforward

Fig. 9 frequency response of vibration measured on the housing

4.2 Results with runout control

When the feedforward controller with LMS algorithm was applied for the rotating frequency (1X), the sensor outputs were measured as Fig. 7. In this tests, the size of trajectories was about 15 ㎛ and 30 ㎛ at front and rear bearing and not changed as speed varied. This shows that the feedforward controller eliminates the effects of the runout so that the sensor output contains only their electrical runout signals. In the Fig. 8, which shows command error *e(t)* with feedforward controller, the magnitude of the command error signals ware measured less than 5 ㎛ including high frequency noise because the runout was effectively eliminated.

The control of runout reduced vibration of spindle as shown in Fig. 9 indicating frequency spectrum of vibration measured at the housing of the spindle. The first order harmonic vibration without runout control shown in Fig. 9(a) was removed after the feedforward controller was applied as in Fig. 9(b). This implies that the forces acting on the radial magnetic bearing of rotational frequency became virtually zero and the shaft was rotating around its center of mass. In this case, the actual rotational displacement of the shaft reduced same as difference between mass and geometrical center, so it was expected to have very high rotational accuracy in well-balanced spindle. These experimental results prove that the feedforward controller is very effective to reduce rotational error and vibration caused by electrical runout of sensor in magnetically suspended spindle system.

5. Conclusion

In this paper, a feedforward controller with LMS algorithm is proposed for rejecting displacement due to electric runout in magnetic bearing system using eddy current sensors. The feedforward controller is designed and examined with its runout rejection performance and stability at all operating speeds by numerical analysis.

Through the experimental results of rotating up to 50,000 rpm with a magnetically suspended grinding spindle, the rotating responses of the sensor were measured about 15 μm and 30 μm at front and rear bearings due to effects of the sensor runout. After applying the proposed runout control, the command error signal was reduced less than 5 μm, and the first order harmonic vibration was removed. These numerical and experimental results show that the proposed feedforward controller with LMS algorithm has effective performance for increasing rotational accuracy and reducing vibration by eliminating electrical runout of the sensor.

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