High Order Disturbance Observer-Based Control For Suspension Active Magnetic Bearing System

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Abstract: This paper presents a high order observer based on the sliding mode controller for a suspension active magnetic bearing system (SAMB). The sliding mode surface is constructed by a proportional-integral-derivative (PID) surface. Due to unable to construct the disturbance mathematical model, the measured disturbance are direct feedback and filtered by a proportional-integral-gain will be revealed by an observer based on input and output signals. In order to improve the output performance, the lump of the uncertainty is estimated by the sliding mode value, these values are feed forward through a low-pass-filter gain. The output results are achieved by Matlab Simulink. The paper is organized as (i) introduction briefly present about the sliding mode and the suspension active magnetic bearing system. (ii) The suspension active magnetic bearing system model is built. (iii) The proposed method are constructed to the system are presented. (iv) The achieved results are given out. (v) Conclusion will be given in this part.

Keywords: Suspension active magnetic bearing (SAMB), sliding mode control (SMC), high order disturbance observer (HODOB), low-pass-filter, proportional – integral filter gain.

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I. Introduction

This paper is aimed to present the high order disturbance performance by apply it to high nonlinear system as a suspension of the magnetic bearing system. In order to imply a high order disturbance observer for nonlinear, the system output and control input are known [1]. The concept of the HODOB in frequency domain was initially revealed by [2-3] proposed High order mismatched disturbance compensation for motion control systems via a continuous dynamic sliding-mode approach. [4] Proposed high order disturbance observer design for linear and nonlinear systems. In order to achieve the desired goals, firstly the sliding mode control (SMC) is mentioned. The SMC was initially developed in mid-1950s, and it was also presented by [5]. Recent few decades the sliding mode control has been received many attention of the scientists. It is a robustness controller, SMC has against ability with output disturbances. The SMC is suitable to construct the controller for high unstable system. Sliding mode control use the difference of the input and output signal to construct the sliding surface. The system state is forced to converge and stabilize on the one pre-determined surface. The velocity and steady-state is depended on how the sliding surface was chosen. There are switching control value and equivalent control value are implemented to converge and stabilize the system state on pre-defined surface, respectively [6]. The chattering values are appeared by high frequency operation of the switching control value. This paper proposes the sliding surface is built by proportional-integral-derivative type. A composed optimization of the proposed method is the lump of the uncertainty is bounded and filtered. The convergence rate of the given output is significantly improved. The controller is applied to control the suspension active magnetic bearing system (SAMB). The SAMB offers many practical applications such as, turbine engines, helicopter and tiltrotor, fly-wheel energy and storage devices, bearingless motor, and vacuum pump, etc.
The Figure. 1 shows the structure of the active magnetic bearing system, there are included rotor is located inside the bearing, and thrust disk is embedded on the rotor. The embedded thrust disk is used to define the rotor position. The original rotor position is refer to $z_0$, and pre-defined position is $z_0 + \zeta$, and $z_0 - \zeta$ respect to the upper and lower magnet coils, respectively. The SAMB mathematical model is given by the next section.

II. Mathematical Modelling Of The SAMB System

According to the Figure. 1, when the coils are supplied the currents the magnetic field surrounds the coils is presented as follows

$$H = \frac{i}{2\pi r}$$

[7-11].This device is referred from our system [7], it is shown in figure below.

$$B = \mu H$$

The Lorentz force acting on an electric charge $Q$ is presented as

$$f = Q(\nabla \times B + E)$$

where $f$ is magnetic force is generated from the electrical charge $\vec{Q}$ and the $\vec{Q}$ is moving with the velocity called $\vec{v}$ in the magnetic flux density, and $\vec{E}$ is electric field.

Because the electric field $E \ll v \times B$, so the Lorentz force is approximated as

$$f = Q(\nabla \times B)$$

The mathematical model of the SAMB is built from the literature [8] as

$$F_1 = \frac{B^2_+ S}{2\mu_0}$$

$$F_2 = \frac{B^2_- S}{2\mu_0}$$

where $B_+$, and $B_-$ are the upper component and the lower component of magnetic density vector. The magnetic force of the SAMB is modelled as
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Using Taylor expansion of the Eq. (7) will leads to

$$F_z = k_p z + k_i z^2$$  \hspace{1cm} (8)

With \( k_p, k_i \) are the amplification factors of the rotor position and the magnet coil currents, respectively. Where

$$k_p = \left. \frac{\partial F_z(z, i_z)}{\partial z} \right|_{z=0,i_z=0} = \frac{2k(l_0 + i_z)^2}{(z_0 - z)^3} - \frac{-2k(l_0 + i_z)^2}{(z_0 + z)^3} = 4k \frac{z^2}{z_0^2 - z^2}$$

$$k_i = \left. \frac{\partial F_z(z, i_z)}{\partial i_z} \right|_{z=0,i_z=0} = \frac{2k(l_0 + i_z)^2}{(z_0 - z)^3} - \frac{-2k(l_0 + i_z)^2}{(z_0 - z)^3} = 4k \frac{i}{z_0^2 - z^2}$$

Follows the Newton II law:

$$m \ddot{z} = F_z(t) - f_{d(t)}$$

where \( m \) is the mass of the inside rotor, \( F_z \) is the Lorentz force, and \( f_{d(t)} \) is the unexpected output disturbance. The Eq. (8) can be written as

$$m \ddot{z} = -z \ddot{z} + k_p z(t) + k_i z^2(t) - f_{d(t)}$$  \hspace{1cm} (9)

or

$$\dot{z}(t) = \frac{1}{m} (-z \ddot{z} + k_p z(t) + k_i z^2(t) - f_{d(t)})$$  \hspace{1cm} (10)

where \( \dot{z} \) is the reference distance value, and \( z_m \) is the measured distance. \( k_p, k_i, k_d \) are positive value and it should be chosen such that the real parts of the roots then sliding surface is satisfied Lyapunov law as

$$V(t) = \ddot{z}(t) \cdot s(t) < 0$$  \hspace{1cm} (14)

Combining Eq. (12) and Eq. (13), the current is calculated as

$$I_{\text{ref}}(t) = \frac{1}{k_d} \int \dot{z}(t) \cdot s(t) dt$$
\[ +k_i \cdot e(t) + k \cdot \text{sign}(s(t)) \] \hspace{1cm} (15)

The chattering value is appeared in the switching control part, in order to reduce these value, this research used saturation function to replace the sign function. Where

\[ \text{sat}(s) = \text{sign}(s) \cdot \min \left[ 1, \frac{\|s\|}{\epsilon} \right] \text{ or } \left\{ \begin{array}{ll} 1 & \text{if } s > \epsilon \\ \frac{1}{\epsilon} & \text{if } s \in [-\epsilon; \epsilon] \\ -1 & \text{if } s < -\epsilon \end{array} \right. \] \hspace{1cm} (16)

Then Eq. (15) can be written as

\[ I_{ref}(t) = \frac{1}{k_d} \left[ z_r(t) - \left( A \cdot \dot{z}_m(t) + B \cdot z_m(t) + d \right) + k_p \cdot e(t) \right] + k_i \cdot e(t) + k \cdot \text{sat}(s(t)) \] \hspace{1cm} (17)

The term of \( k \cdot \text{sat}(s(t)) \) is called switching control part, there are chattering appeared. Due to unable directly to estimate the uncertainty of the system [13], this paper proposes the uncertainty estimator based on the sliding mode surface. Firstly, the system from Eq. (9) need to be modified as

\[ \dot{x} = (G_{In} + \Delta G_1) \cdot x + (G_{2n} + \Delta G_2) \cdot i + G_3 \cdot d \] \hspace{1cm} (18)

or

\[ \dot{x} = (G_{In}) \cdot x + (G_{2n}) \cdot i + L + G_3 \cdot d \] \hspace{1cm} (19)

where lump of the uncertainty is \( L = \Delta G_1 \cdot x + \Delta G_2 \cdot i \). basically, the derivative of the sliding mode surface is

\[ s_{in} = -k \cdot \text{sat}(s_{in}) \] \hspace{1cm} (20)

or

\[ s_{in} = -L - u_L(t) - k \cdot \text{sat}(s_{in}) \] \hspace{1cm} (21)

where \( L = -u_L(t) \). The lump of uncertainty can be observed by a filter. A suggestion of strictly proper low-pass filter is \( G_f(s) \), the lump of the uncertainty can be approximated by

\[ \hat{L} = L^{-1} \left[ G_f(s) \right] \left( -u_L(t) - k \cdot \text{sat}(s_{in}) - s_{in} \right) \] \hspace{1cm} (22)

where \( L^{-1} \left[ \bullet \right] \) is the inverse Laplace transfer function, and \( \times \text{sign} \) is convolution operator. Substituting \( L = -u_L(t) \) to Eq. (22) yields

\[ u_L(t) = L^{-1} \left[ \frac{G_f(s)}{1 - G_f(s)} \right] \left( k \cdot \text{sat}(s_{in}) + s_{in} \right) \] \hspace{1cm} (23)

The control signal is improve as

\[ V_c(t) = V_{0c} + L^{-1} \left[ \frac{G_f(s)}{1 - G_f(s)} \right] \left( k \cdot \text{sat}(s_{in}) + s_{in} \right) \] \hspace{1cm} (24)

Then choose \( G_f(s) = \frac{1}{1 + Ts} \) as a filter, then

\[ V_c(t) = V_{SMC} + \left( k \cdot \text{sign}(s) + k \cdot \int \text{sat}(s(t)) \text{d}t \right) \] \hspace{1cm} (25)

The stability of the uncertainty estimation as following

\[ s \cdot s(s) = -k \cdot s(s) - \left[ 1 - G_f(s) \right] L(s) \] \hspace{1cm} (26)

or

\[ s(s) = k_d \cdot s \cdot e(s) + k_p \cdot e(s) + k_i \cdot \int \frac{1}{s} \cdot e(s) \] \hspace{1cm} (27)

Substituting Eq. (27) to Eq. (26) yields

\[ e(s) = \frac{s}{s + k} \frac{G_f(s) - 1}{k_d \cdot s^2 + k_p \cdot s + k_i} \cdot L(s) \] \hspace{1cm} (28)
On the time domain the distance tracking error are

\[ \lim_{t \to \infty} (e(t)) = \lim_{s \to 0} s \frac{G_f(s) - 1}{s^2 k_d s^2 + k_p s + k_i} \cdot L(s) \]  
\[ = 0 \]  

(29)

**High order disturbance observer design.**

Estimation of the unknown disturbance has been interest topic in recent decades [12]. Many article published the performance of this topic research [14-17]. The disturbance observer (DOB) were introduced early in 1980s[18]. Since the day the DOB was appeared, many article applied it successfully. In process control [18], in mechatronic [19-21]. Our proposed a disturbance observer based system states for linear system [11], there are proportional-integral filter gains are applied to force system state converge on the stable region by choosing suitable parameter. In this paper the high order disturbance observer will be appeared, the structure of the controller are the disturbance will be filtered by a proportional-integral gain, and the disturbance error is approximated by a low-pass-filter gain. The system model from Eq. (19) will be modify by

\[ \hat{d}(t) = \hat{d}_d - \hat{d} \]  
\[ \hat{d} = \text{diag} \{r\} \cdot \{F^+ \cdot x + \chi \} \]  
\[ \hat{d}_d = \text{diag} \{r\} \cdot \{F^+ \cdot L(t) + d(t)\} \]  
\[ \hat{d}_d = \text{diag} \{r\} \cdot \{F^+ \cdot L(t) + d(t)\} \]  

(30)

where \( F^+ \cdot G_3 = I \). the disturbance observer system are

The Eq. (34) shows that the \( \hat{d}(t) \to \frac{d}{dt} \hat{d}(t) \) depending on the filter gain. The \( \hat{d}(t) \) is depending on the matched uncertainty term. By choosing suitable \( \text{diag} \{r\} \) to reality application of the proposed method to system as
where \(u_{\text{lump}}\) and \(u_d\) are the feedback value of uncertainty and disturbance value, the output of filter gain are

\[V_c(t) = V_{\text{SMC}} + \left( \frac{k}{T} \cdot \text{sat}(s) + k \cdot \int_0^t \text{sat}(s(t)) dt \right) + k_p \cdot \hat{d} + k_f \int_0^t \hat{d}(\tau) \cdot d\tau + L^{-1} \{G_f(s)\} \cdot (d - \hat{d}) \tag{36}\]

By choosing a suitable low-pass-filter gain for disturbance error part the lump of disturbance error are

\[u_{d-\hat{d}} = \frac{1}{T} \cdot e^{-\frac{t}{T}} \tag{37}\]

\[u_{d-\hat{d}} \to 0 \text{ when } t \to \infty \text{ with a suitable time constant of the filter gain. When the observer of disturbance is constructed a proportional-integral the disturbance are}

\[\hat{d} = k_p \cdot \text{diag} \{r\} \cdot \left\{F^{+} - x + z\right\} + k_I \cdot \int_0^t \text{diag} \{r\} \cdot \left\{F^{+} - x + z\right\} dt \tag{38}\]

Taking derivative of the disturbance leads to

\[\dot{\hat{d}} = k_p \cdot \text{diag} \{r\} \cdot \left\{F^{+} - x + z\right\} + k_I \cdot \text{diag} \{r\} \cdot \left\{F^{+} - x + z\right\} \tag{39}\]

In order to \(\hat{d} \to d\) the \(k_I\), and \(k_p\) are reasonable choose. Then, the performance of the proposed method are below.

### IV. An illustrative Example

In order to emphasize the powerful of the proposed technics, this part describes the given output of the proposed method under two cases

**Case 1:** The results without using the disturbance error feedback.

In this case, the proposed controller is sliding mode control and high order disturbance observer with a proportional-integral filter gain. The given output results are good track with the sinusoidal signal. The given output signal of this case are presented as
Figure 3 The proposed control method without using the disturbance error feedback: (a) The distance response signal in first 20s, (b) The distance response signal at first 0.1s, (c) The distance tracking error value, (d) The top value of the distance tracking error value, (e) The disturbance response signal.

Case 2: The results while the full disturbance and disturbance error are used.
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(b)

(c)

(d)

(e)
The proposed controller is good at tracking the flexible reference input signal. In the case of the paper, the disturbance observer with a proportional filter gain given a good performance, but not very well smoothly. It has been improved by equipped a disturbance error feedback control. There are included a term of uncertainty value. These values are filter by a low-pass-filter to achieve the desired goals. This result is better much more than our previous published paper [7]. Every given output of this proposed method has been improved significantly.

V. Conclusion

The proposed controller is good at tracking the flexible reference input signal. In the case of the paper, the disturbance observer with a proportional filter gain given a good performance, but not very well smoothly. It has been improved by equipped a disturbance error feedback control. There are included a term of uncertainty value. These values are filter by a low-pass-filter to achieve the desired goals. This result is better much more than our previous published paper [7]. Every given output of this proposed method has been improved significantly.

Reference


Figure. 4 The proposed control method without using the disturbance error feedback: (a) The distance response signal in first 20s, (b) The distance response signal at first 0.1s, (c) The distance tracking error value, (d) The top value of the distance tracking error value, (e) The disturbance response signal, (f) The lump of Uncertainty value.

In comparison of the two cases give out briefly understanding knowledge that, the proposed controller is good at tracking flexible signal, it has ability to against the uncertainty, and good estimated disturbance is given out. The improvement of the disturbance error feedback through two terms are significantly performed at Figure. (4). the settling time is improved from 16.725(ms) to 2715(ms), distance tracking error value has been improved from \(2.12 \cdot 10^{-5}\) (mm) to \(1.86 \cdot 10^{-5}\) (mm), and the top of the disturbance error tracking value also been reduced from \(0.03915\) (mm) to \(1.2 \cdot 10^{-3}\) (mm) by applying the disturbance feedback method.
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Appendix
The system parameters of suspension AMB system, and controller parameters are given by tables below.

Table. 1 System parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>Mass of rotor</td>
<td>2.565</td>
<td>kg</td>
</tr>
<tr>
<td>$k_{ai}$</td>
<td>Current stiffness of Electromagnetic force of Thrust disk AMB</td>
<td>40</td>
<td>N / A</td>
</tr>
<tr>
<td>$k_{ap}$</td>
<td>Position stiffness of electromagnetic force of thrust disk AMB</td>
<td>25200</td>
<td>N / m</td>
</tr>
<tr>
<td>$z_0$</td>
<td>Nominal air gap where thrust disks centred</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>r</td>
<td>Thrust disk mass</td>
<td>0.38</td>
<td>kg</td>
</tr>
<tr>
<td>c</td>
<td>Damping constant</td>
<td>0.001</td>
<td>N·s/m</td>
</tr>
<tr>
<td>$v_0$</td>
<td>Reference voltage</td>
<td>1.4</td>
<td>V</td>
</tr>
<tr>
<td>$i_0$</td>
<td>Amplifier range</td>
<td>0.5</td>
<td>A/V</td>
</tr>
</tbody>
</table>

Table. 2 The controller parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p$</td>
<td>Proportional coefficient</td>
<td>3000</td>
</tr>
<tr>
<td>$k_i$</td>
<td>Integral coefficient</td>
<td>5000</td>
</tr>
<tr>
<td>$k_d$</td>
<td>Derivative coefficient</td>
<td>1</td>
</tr>
<tr>
<td>$k$</td>
<td>Positive gain</td>
<td>30</td>
</tr>
<tr>
<td>$T$</td>
<td>Low-pass-filter time</td>
<td>0.001</td>
</tr>
<tr>
<td>$k_p'$</td>
<td>PI filter gain</td>
<td>0.9</td>
</tr>
<tr>
<td>$k_i'$</td>
<td>PI filter gain</td>
<td>0.01</td>
</tr>
<tr>
<td>diag(r)</td>
<td>Observer gain</td>
<td>diag(1, 500)</td>
</tr>
</tbody>
</table>

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