ADAPTIVE FRICTION COMPENSATION OF SERVO MECHANISMS WITH NONLINEAR VISCOUS FRICTION

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ABSTRACT
In this paper, a SDOF system with nonlinear viscous friction under harmonic excitation is studied. A nonlinear viscous friction model is built as an exponential expansion of the relative slip velocity. According to the adaptive control theory, an adaptive controller for the friction compensation of the SDOF system with nonlinear viscous friction is put forward by using the model-based parameterization techniques. The good performance of the proposed control scheme is illustrated through the computer simulation.

INTRODUCTION
Friction compensation is an important research topic in the field of motion control of mechanical systems with friction. There have been many works on model-based friction compensation [1,2]. The accuracy of the fixed friction compensation is always affected by the parameter estimation of friction model. So the application of fixed friction compensation is limited by its shortcomings. The adaptive friction compensation has been an important branch among the many model based friction compensation methods [3,4]. The principal advantage of adaptive friction compensation relative to the fixed compensation lies in its ability to track changes in friction. Viscous friction is the most popular ingredient in friction model utilized for control of mechanical systems. From the research works on friction compensation, the adaptive friction compensation methods are all concentrated on the linear viscous friction, in which the viscous friction is considered as a linear function of velocity. While the friction compensation about nonlinear viscous friction in mechanical systems is seldom considered at present. In this paper the adaptive friction compensation theory is introduced to the mechanical system with nonlinear viscous friction based on the present research works on the nonlinear viscous friction. The adaptive friction compensation controller of mechanical system with nonlinear viscous friction is presented.

This paper is organized as follows: In Section 1 the nonlinear viscous friction model is introduced. In Section 2 the adaptive friction compensation for nonlinear viscous friction is put forward. Simulation example is used to demonstrate the performance of the addressed method. Conclusions are drawn in the last.

NOMENCLATURE
Adaptation error = $\dot{\theta}_i (i = 1, 2, 3)$
Adaptation gain = $\gamma$
Adaptive parameter = $\hat{\theta}_i (i = 1, 2, 3)$
Applied force input = $f$
Arbitrary large numbers = $n, q$
Coefficients = $c, c_{\mu}$
Coulomb friction = $h$
Desired position = $x_d$
Differential gain = $k_d$
Elastic element = $F_e (x)$
Exciting signal = $p(t)$
Mass = $m$
Nonlinear viscous friction = $F_{vd} (\dot{x})$
Observer gain = $\kappa$
Position = $x$
Position error = $e$
Proportional gain = $k_p$
Stiffness = $k$

METHODS
1 Nonlinear viscous friction model
The nonlinear viscous friction model has been put forward in paper [5,6]. The nonlinear viscous friction model is a function of exponential expansion of velocity. The viscous friction coefficients are identified using the energy balance method. The nonlinear viscous friction model in paper [5] is introduced in this paper. The differential equation of motion for the SDOF system with nonlinear viscous friction can be written

\[ m\ddot{x} + F(x,\dot{x}) = p(t) \]  

(1)

where, \( F(x,\dot{x}) = F_d(\dot{x}) + F_s(x) \), \( F_d(\dot{x}) = h \text{sgn}(\dot{x}) + \sum_{i=1}^{n} c_i \dot{x}^i \), \( F_s(x) = \sum_{\mu=1}^{q} c_{\mu} x^\mu \), \( F_d(\dot{x}) \) is the nonlinear viscous friction model. \( F_s(x) \) is purely elastic element. \( p(t) \) is the exiting signal. The Eq.(1) can be rewritten

\[ m\ddot{x} + h \text{sgn}(\dot{x}) + \sum_{i=1}^{n} c_i \dot{x}^i + \sum_{\mu=1}^{q} c_{\mu} x^\mu = p(t). \]  

(2)

Where, \( h \) is coulomb friction, \( n, q \) are arbitrary large numbers.

2 Adaptive friction compensation

The nonlinear viscous friction is only considered in this paper. Let \( n = 5 \) and \( \mu = 1 \), the Eq. (2) is expressed as

\[ m\ddot{x} + c_1 \dot{x} + c_2 \dot{x}^2 + c_3 \dot{x}^3 + c_5 \dot{x}^5 + kx = p(t). \]  

(3)

where, \( c_1, c_3, c_5 \) are the coefficients, \( k \) is the stiffness. The adaptive law about the nonlinear viscous friction based on the paper [7] is given:

\[ f = k_p e + k_v \dot{e} + \dot{\theta}_1 \dot{x} + \dot{\theta}_2 \dot{x}^2 + \dot{\theta}_3 \dot{x}^3 + \dot{\theta}_5 \dot{x}^5 + m\ddot{x}_d \]  

(4)

where, \( f \) is the applied force input, \( e = x_d - x \) is position error, \( x_d \) is the desired position, \( k_p, k_v \) is proportional gain and differential gain. The adaptive control laws about \( \theta_1, \theta_2, \theta_3 \) are given

\[ \dot{\theta}_1 = \gamma (\dot{e} + \kappa e) \]  

(5)

\[ \dot{\theta}_2 = \gamma \dot{e} (\dot{e} + \kappa e) \]  

(6)

\[ \dot{\theta}_3 = \gamma \dot{e}^3 (\dot{e}^3 + \kappa e^3) \]  

(7)

The differential equation of SDOF system is

\[
\begin{bmatrix}
\ddot{\bar{e}} \\
\dot{\bar{e}} \\
\dot{\bar{\dot{e}}} \\
\dot{\bar{\ddot{e}}}
\end{bmatrix} =
\begin{bmatrix}
\ddot{e} \\
\dot{e} \\
-1/m[k_p \dot{e} + k_v \ddot{e} + \dot{\theta}_1 \dot{x} + \dot{\theta}_2 \dot{x}^2 + \dot{\theta}_3 \dot{x}^3 + \dot{\theta}_5 \dot{x}^5] \\
\end{bmatrix}
\]

(8)

\[
\begin{bmatrix}
\ddot{\bar{e}} \\
\dot{\bar{e}} \\
\gamma (\dot{\bar{e}} + \kappa \bar{e}) \\
\gamma \dot{e} (\dot{\bar{e}}^3 + \kappa \bar{e}^3) \\
\gamma \dot{e} (\dot{\bar{e}}^5 + \kappa \bar{e}^5)
\end{bmatrix}
\]

where, \( \bar{\dot{\theta}} = \dot{\theta}_1 - c_1 \), \( \bar{\dot{\theta}} = \dot{\theta}_2 - c_2 \), \( \bar{\dot{\theta}} = \dot{\theta}_3 - c_3 \), \( \gamma > 0 \) is adaptation gain, \( \kappa > 0 \) is the observer gain.

SIMULATION

In this section, the simulation example in paper [5] is adopted. The equation of SDOF system with nonlinear viscous friction is

\[ m\ddot{x} + F_d(\dot{x}) + F_s(x) = p(t), \]

where, \( F_d(\dot{x}) = kx \), \( F_s(x) = c_1 \dot{x} + c_2 \dot{x}^2 + c_5 \dot{x}^5 \). The original data are: the mass \( m = 8kg \), the stiffness \( k = 9800kg/s^2 \), the nonlinear viscous friction coefficients are \( c_1 = 260kg/s \), \( c_2 = -340kg/s^2 \), \( c_5 = 320kg/s^3/m^4 \). The desired position is \( x_d = 10\sin(2\pi t) \), the controller gains are: \( k_p = 10Nm/rad \), \( k_v = 1.2Nm/rad \). The simulation result is shown in Fig.1.

CONCLUSIONS

The viscous friction effect is particularly harmful among the various ingredients present in the friction compensation. The nonlinear viscous friction model is investigated in the paper. The adaptive friction compensation theory is applied to the servo mechanism with nonlinear friction. The simulation result is satisfactory. It is shown that the adaptive friction compensation can be applied to the mechanical system with nonlinear viscous friction, and the adaptive friction compensation method is effective for the nonlinear viscous friction.

ACKNOWLEDGMENTS

The authors acknowledge the financial support by National Natural Science Foundation of China (No.50075068).

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