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Time series analysis of electrorheological actuator with double driving discs

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Abstract: An electrorheological(ER) actuator with double driving discs rotating at the same speed in the opposite directions was designed for studying the electrorheological torque experiments. The dynamic model of the disc transmission system consists of the linear part between the output angle and the electric torque, and the nonlinear part between the electric torque and the applied field strength dependent on the ER fluids. Using only the output sampled torque signals, an autoregressive model, the auto-spectral density function, the autoregressive(AR) bispectrum and the slices of the bispectra, taken to analyse the torque dynamic response, are obtained when a zero mean and non-Gaussian white noise interferes with the rotary disc system. The method for AR model order selection based on bispectral cross correlation is proposed and employed to determinate the model order. The experimental and theoretical results show that the time series analysis method and the parametric bispectrum might be helpful to establish the dynamic model of an ER actuator and to quantitatively analyse the torque response.

Key words: electrorheological fluids; dynamic model; disc actuator; time series analysis

1 Introduction

One of new ER devices proposed for transmission mechanisms is the disc-shaped actuator utilizing ER fluids. The interest in studying the torque transmission characteristics lies on the fact that they are important to operate of many devices, such as a clutch, a brake, a rotary damper, a disc-shaped rheometer and a servo control device. The focus of this paper is to develop a fundamental understanding of mechanical properties of ER fluids in a pair of rotary discs. Therefore an ER actuator with double driving discs rotating at the same speed in the opposite directions was designed for studying the electrorheological torque experiments.

The bispectrum has recently been widely used as an important technology for signal processing, which can describe nonlinear coupling, restrain Gaussian noise and reserve phase component. A number of studies of electrorheological actuator is pursued for modeling by using the spectral and other approaches, but none of these offer parametric bispectral analysis of an electrorheological actuator. However, the correlation studies of bispectral analysis are helpful to this topic. BHATTACHARYA et al[1] designed an algorithm for AR modeling any arbitrary 2-D data string. YANG et al[2] addressed the development of a novel condition monitoring procedure for rolling element bearings which involves a combination of signal processing, signal analysis and artificial intelligence methods. SHEN et al[3] analyzed heart sound signals by applying higher-order spectral technique.

Assuming that a zero mean and non-Gaussian white noise interferes with the electrorheological rotary system and using the diagonal slices of the third-order cumulant matrix of the sampled data, the time series models are proposed for describing the ER fluids utilized in the actuator. AR bispectra of the sampled data are given for studying torque dynamic response.

2 ER torque between pair of rotary discs

A pair of rotary discs used for studying torque dynamic response is shown in Fig.1. The ER actuator with double driving discs rotating at the same speed in the opposite directions can be used for pure electric toque experiment because that the viscous torques caused by the two driving discs are counteractive. The dynamic model of the rotary discs is composed of two parts: 1) a linear part between the output angle and electric torque, and 2) a nonlinear part between the electric torque and the applied field strength dependent on the ER fluids.

As shown in Fig.1, a pair of rotary discs, between which ER fluids is filled in the space, is applied electric field. The left disc has driving angular velocity Ω_l and right disc has driving angular velocity Ω_r.

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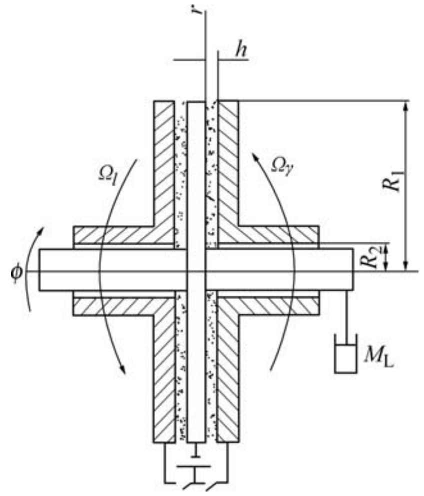

Fig.1 A pair of rotary discs

The shear stress τ vs shear rate $\dot{\gamma}$ behavior approximates that of power law fluids:

$$\tau = \eta_a(E, \dot{\gamma})\dot{\gamma} \tag{1}$$

where η_a is the apparent viscosity and can be represented by

$$\eta_a(E, \dot{\gamma}) = k(E)\dot{\gamma}^{n(E)-1} \tag{2}$$

where $k(E)$ is the consistency, $n(E)$ is the index number, which are functions of the strength of electric field E.

The torque generated by a pair of rotary ER discs consists of two components: the torque M_η from the viscosity of the ER fluids and the torque M_e owing to the field-dependent yield shear stress, i.e. the total torque M_{so} is

$$M_{so}=M_e+M_\eta \tag{3}$$

And the field-dependent torque M_e is

$$M_e = \frac{2\pi k(E)}{n(E)+3}\left(\frac{\Delta\Omega}{h}\right)^{n(E)} R_2^{n(E)+3}\left[1-\left(\frac{R_1}{R_2}\right)^{n(E)+3}\right] - \frac{\pi\eta}{2}\left(\frac{\Delta\Omega}{h}\right)R_2^4\left[1-\left(\frac{R_1}{R_2}\right)^4\right] \tag{4}$$

where R_1 is the inner radius of the disc; R_2 is the outer radius of the disc; $\Delta\Omega$ is the difference between the driving angular velocity, Ω_i, and the driven velocity, Ω_0; h is the electrode space.

From Eqn.(4) it is clear that the relation between ER torque and the applied field strength E is nonlinear and Eqn.(4) is only used to describe the static state. People interest in the dynamic response of electrorheological moment transmission[4]. When a zero mean and non-Gaussian white noise interferes with the rotary disc system, the dynamic moment transmission can be founded using the output sampled torque signals only.

3 Experimental equipment

An antagonistic rotary disc-shaped ER actuator is manufactured and the measurement setup is shown schematically in Fig.2. The actuator is composed of centric disc, which couples to output shafts, and left and right driving discs. The left disc is driven through a synchronous belt by an adjustable-speed motor, and the right disc is rotated through a pair of reversing gears and other synchronous belt at the same speed in the opposite

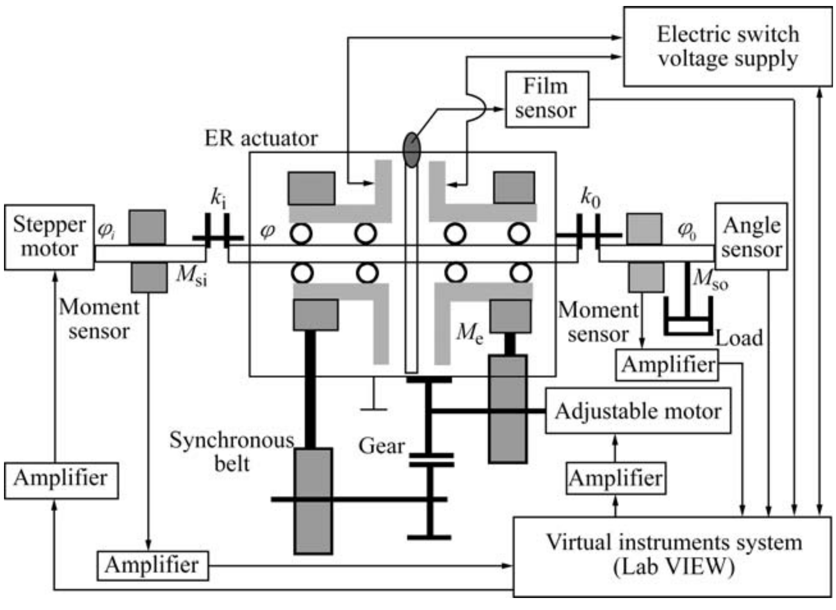

Fig.2 Work principle of ER actuator system

directions by the same motor. The ERF is filled in the gaps between the centric disc and driving discs. Same size electrodes are set on each disc. The output torque of ER actuator is controlled by changing the application of electric field between the centric disc and left/right driving disc. The centric disc is made of aluminum alloy in order to reduce the moment of inertia of the output shaft.

Since torque response times are on the order of milliseconds, arrangements have to be made to switch the power supplies fast about 1 ms. A film sensor is used to detect the temperature. The output torque, angular velocities are detected by the angular moment sensors at the couple. The whole detecting, analyzing and controlling system applies NI virtual instruments system and controlled by computer automatically.

The input angular velocity Ω_i, input moment M_{si} and output moment M_{so} in the experiments under the applied electric field for the exponent and sinus input velocities are plotted in Fig.3(a) and Fig.4(a). The output moments M_o, whose certain signals have been eliminated, are plotted in Fig.3(b) and Fig.4(b) correspondingly. The AR models can be established by using the colored noises in the out moments, M_o.

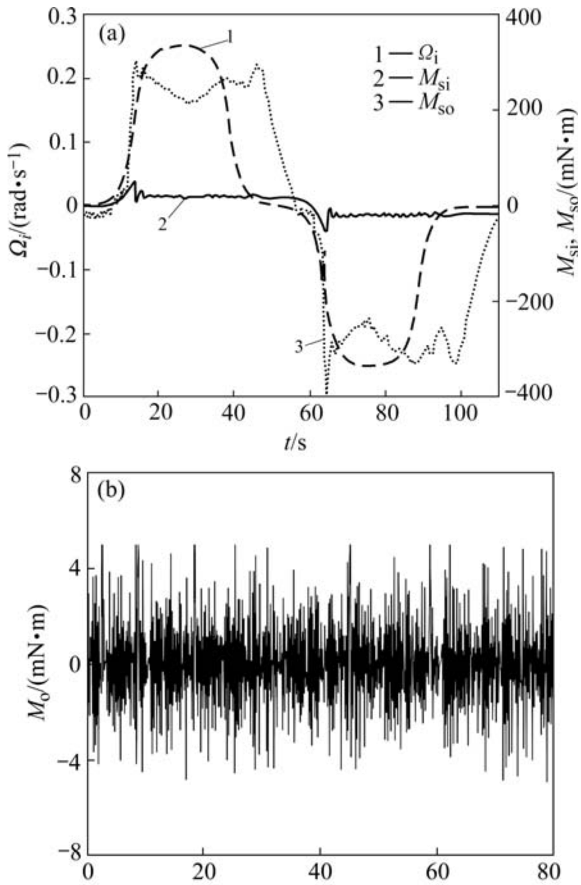

Fig.3 Sampled signals for exponent velocity input
(a) Input velocity and moments;
(b) Colored noise in out moment M_o

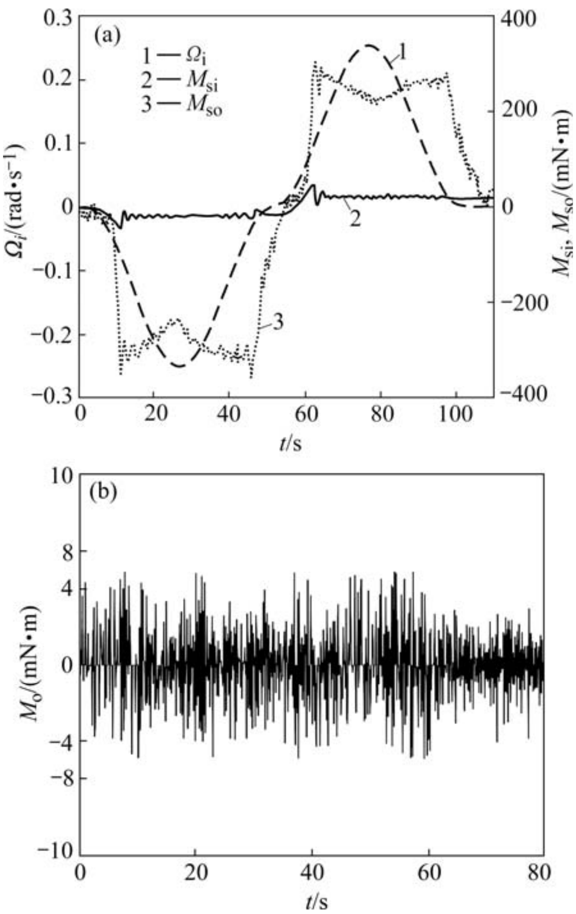

Fig.4 Sampled signals for sinus velocity input
(a) Input velocity and moments;
(b) Colored noise in out moment M_o

4 Autoregressive model

For modeling purposes, the zero mean colored noise, $M_o(t)$, is assumed to be the output of an autoregressive process driven by a noise $a(t)$.

The AR model can be written as follows:

$$M_o(t) + \sum_{i=1}^{p} \alpha_i M_o(t-i) = a(t)$$

$$t=1, 2, \cdots, N \tag{5}$$

where p is the order of the AR model. The input signal $a(t)$ has the following properties:

1) $a(t)$ is non-Gaussian ;

2) $E(a(t))=0$;

3) $E\{a(t)a(t+m)\} = \sigma_\alpha^2 \delta(m)$, where $\delta(m)$ is pulse function;

4) $E\{a(t)a(t+m)a(t+n)\}=\beta\delta(m, n)$, where $\delta(m, n)$ is two-dimension pulse function;

5) $E\{M_o(t-m)a(t)\}=0$, $(m>p)$.

The third-order cumulant of the signal $M_o(t)$ is then[5]

$$C[M_o(t)M_o(t+m)M_o(t+n)]=E\{M_o(t)M_o(t+m)M_o(t+n)\} \quad (6)$$

Eqn.(6) can be rewritten in terms of m and n as

$$C[m, n]=E\{M_o(t)M_o(t+m)M_o(t+n)\} \quad (7)$$

Mathematically, from Eqn.(5), representing a steady process, the AR model of cumulant can be obtained.

$$C[-m,-n]+\sum_{i=1}^{p}\alpha_i C[-m+i,-n+i]=\beta\delta(m,n)$$

$$(m,\ n\geqslant 0) \quad (8)$$

Varying m and n from 0 to p and assuming that $m=n$, a set of $(p+1)$ equations can be generated. When written in matrix form, the equations become

$$\boldsymbol{CA}=\boldsymbol{B} \quad (9)$$

where

$$\boldsymbol{C}=\begin{bmatrix} C(0,0) & C(1,1) & \cdots & C(p,p) \\ C(-1,-1) & C(0,0) & \cdots & C(p-1,p-1) \\ C(-2,-2) & C(-1,-1) & \cdots & C(p-2,p-2) \\ \vdots & \vdots & \vdots & \vdots \\ C(-p,-p) & C(-p+1,-p+1) & \cdots & C(0,0) \end{bmatrix} \quad (10)$$

$$\boldsymbol{A}=[1, \alpha_1, \alpha_2, \cdots, \alpha_p]^{\mathrm{T}} \quad (11)$$

is the coefficient vector, and

$$\boldsymbol{B}=[\beta, 0, 0, \cdots, 0]^{\mathrm{T}} \quad (12)$$

Eqn.(9) can be solved using the $(2p+1)$ diagonal slices, $C(m, n)$, with simple matrix inversion method, to generate the parameter vector $\boldsymbol{A}$ and β.

The thing that is required to be known at this stage is the model order, p. Here the method for AR model order selection on bispectral cross correlation is proposed and applied.

5 AR auto-spectral density function

The auto-spectral density, $S(\omega)$, is defined as the Fourier transform of the autocorrelation function, $R(k)$, i.e.

$$S(\omega)=\sum_{k=-\infty}^{\infty}R(k)\exp(-jk\omega) \quad (13)$$

where $\omega=2\pi f$, f is sampling frequency. The $S(\omega)$ can be expressed in frequency transfer function $H(\omega)$,

$$S_{xx}(\omega)=\sigma_a^2 H(\omega)H^*(\omega) \quad (14)$$

Therefore the AR auto-spectral density, $S^{\mathrm{AR}}(\omega)$, is given by

$$\left|S^{\mathrm{AR}}(\omega)\right|=\frac{\sigma_\alpha^2}{\left|1+\sum_{i=1}^{p}\alpha_i\exp(-ji\omega)\right|} \quad (15)$$

Since the $S^{\mathrm{AR}}(\omega)$ determined by statistic quantities α_i (i=1, 2, ···, p), is the square of the frequency response function, the curves (shown in Fig.5(b), Fig.5(c), Fig.6(b) and Fig.6(c)) are more smoother than Fourier's curves. In Eqns.(14) and (15) the phase information is suppressed so that auto-spectrum function cannot obtain

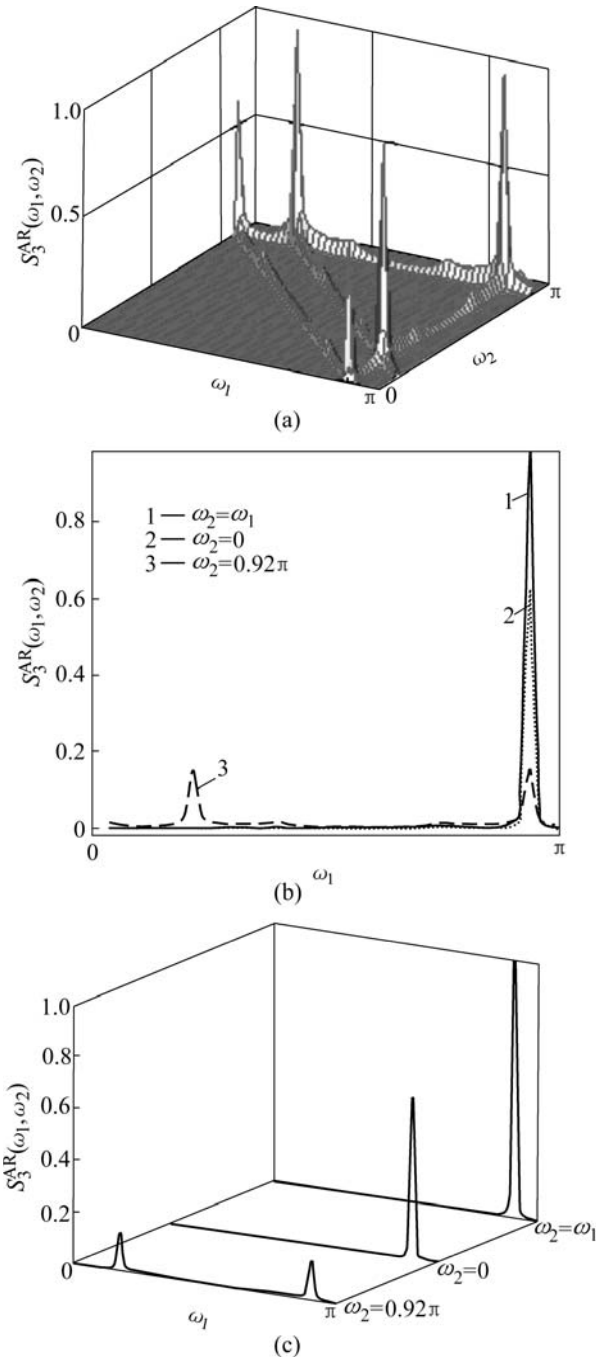

Fig.5 Bispectrum for exponent function input
(a) Bispectrum; (b) Some slices; (c) Slices

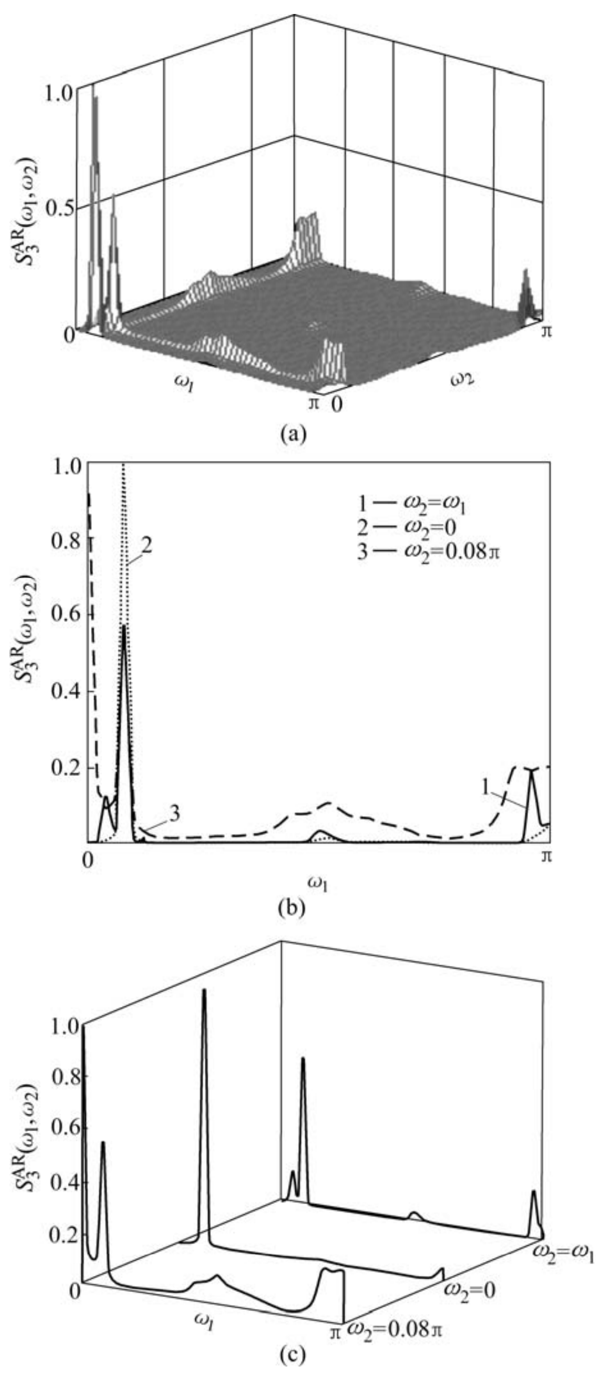

Fig.6 Bispectrum for sinus function input
(a) Bispectrum; (b) Some slices; (c) Slices

the phase relationship between different frequency components.

6 Autoregressive bispectrum

The signal's bispectrum is defined by the following equation:

$$B(\omega_1,\ \omega_2)=\sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty}C(m,n)\exp[-j(\omega_1 m+\omega_2 n)] \quad (16)$$

where $|\omega_1|\leqslant\pi$, $|\omega_2|\leqslant\pi$ and $|\omega_1+\omega_2|\leqslant\pi$.

Rewriting Eqn.(16) in terms of frequency characteristic functions gives

$$B(\omega_1,\ \omega_2)=F(\omega_1)F(\omega_2)F^*(\omega_1+\omega_2) \quad (17)$$

In the case in which $F(\omega)$ is $M_o(t)$ Fourier transform. Thus $B(\omega_1,\ \omega_2)$ is the complex function, which can be adopted to yield information about the amplitude $|B(\omega_1,\omega_2)|$ and phase $\angle B(\omega_1,\omega_2)$, i.e.

$$B(\omega_1,\omega_2)=|B(\omega_1,\omega_2)|\exp[j\angle B(\omega_1,\omega_2)] \quad (18)$$

where $\angle B(\omega_1,\omega_2)$ is called the biphase.

AR bispetrum, $S_3^{AR}(\omega_1,\omega_2)$, is determined from the following equation[6−7]:

$$S_3^{AR}(\omega_1,\omega_2)=\beta H(\omega_1)H(\omega_2)H^*(\omega_1+\omega_2) \quad (19)$$

The normalized bispectra and some bispectrum slices are illustrated in Fig.5 and Fig.6 corresponding to exponent and sinus inputs. According to the definition of bispectrum and comparing Fig.5 with Fig.6, it is indicated that:

1) The largest peaks can be found in the each plot and are due to the elastic couplings of the actuator. However, the variation in the bispectrum is more evident than those for the power spectrum because the sensitivity of the bispectrum is higher than that of the power spectrum.

2) In the inner triangular domain $\omega_2\geqslant 0$, $\omega_1\geqslant\omega_2$ and $\omega_1+\omega_2\leqslant\pi$, the spectrum is sufficient for the description of the bispectrum characteristics, since, due to symmetry in the ω_1-ω_2 plane of the bispectrum, all of the useful information is contained in the principal region.

3) The differences between the AR auto-spectrum density (corresponding to ω_2=0) and the AR bispectrum can be seen easily by observing the distributions of the both spectral magnitudes. The AR bispectrum provides information about the phase coupling between three frequencies ω_1, ω_2, $\omega_1+\omega_2$. Therefore, the energy displayed in the bispectrum reveals more than does the AR auto-spectrum density.

4) In the inner triangular domain, which is described at 2), the peaks of bispectra occur at $\omega_1\approx 0.92\pi$ for the exponent function velocity input, and at $\omega_1\approx 0.08\pi$ for the sinus function velocity input. The different peak distributions show that the phase coupling is dependent on the configuration of the actuator and the operation.

7 Conclusions

Electrorheological actuator system is a nonlinear mechanical transmission system. Establishing the mathematic model and analyzing the torque dynamic response are important to design electrorheological actuator and control the system. A double driving rotary disc-shaped actuator of ER fluids is developed. The dynamic response experiments are presented. Above experiments and the time series analysis demonstrate that:

1) The electrorheological actuator with double driving discs rotating at the same speed in the opposite directions can be used for pure electric toque experiment because that the viscous torques caused by the two driving discs are counteractive.

2) When a zero mean and non-Gaussian white noise interferes with the electrorheological rotary discs system, an AR model can be established. The use of third-order cumulants, estimated by the output sampled moment signals, for modeling purpose eliminates additive Gaussian noise and provides the information of phase coupling.

3) The measurement and analysis system with fast response speed and high accuracy is established on NI virtual instruments. The system is also a new universal experimental platform, on which many experiments of electromechanical engineering can be carried out.

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