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Vibration Control of the Rotating Machine Geared Drive System Using Linear Actuators with the Magneto-Rheological Fluid

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Abstract

In this paper there is proposed a semi-active control technique based on the linear actuators with the magneto-rheological fluid (MRF) connecting the drive system planetary gear housing with the immovable rigid support. Here, control damping torques are generated by means of the magneto-rheological fluid of adjustable viscosity. Such actuators can effectively suppress amplitudes of severe transient and steady-state rotational fluctuations of the gear housing position and in this way they are able to minimize dangerous oscillations of dynamic torques transmitted by successive shaft segments in the entire drive system. The general purpose of the considerations is to control torsional vibrations of the real power-station coal-pulverizer geared drive system driven by means of the asynchronous motor. The investigations have been carried out using the experimental test rig based on the real object, where the measurement results were compared with analogous theoretical ones obtained by the use of computer simulations.

Keywords: torsional vibrations, magneto-rheological dampers, semi-active control

1. Introduction

Active vibration control of drive systems of rotating machines, mechanisms and vehicles creates new possibilities of improvement of their effective operation. Torsional vibrations are in general rather difficult to control not only from the viewpoint of proper control torque generation, but also from the point of view of a convenient technique of imposing the control torques on quickly rotating parts of the drive-systems and rotor machines. Unfortunately, one can find not so many published results of research in this field, beyond some attempts performed by an active control of shaft torsional vibrations using piezo-electric actuators, see [4]. But in such cases relatively small values of control torques can be generated and thus the piezo-electric actuators can be usually applied to low-power drive systems.

Thus, for drive systems of high-power machines, mechanisms and vehicles in this paper there is proposed the semi-active control technique based on the linear actuators with the magneto-rheological fluid (MRF) connecting the drive system planetary gear housing with the immovable rigid support. The control torques are generated by means of the magneto-rheological fluid of adjustable viscosity. They interact with reaction torques transmitted by the planetary gear housing due to torsional vibrations of the drive system. Such actuators can effectively suppress amplitudes of severe transient and steady-state rotational fluctuations of the gear housing position and in this way they are able to minimize dangerous oscillations of dynamic torques transmitted by successive shaft segments in the entire drive system.

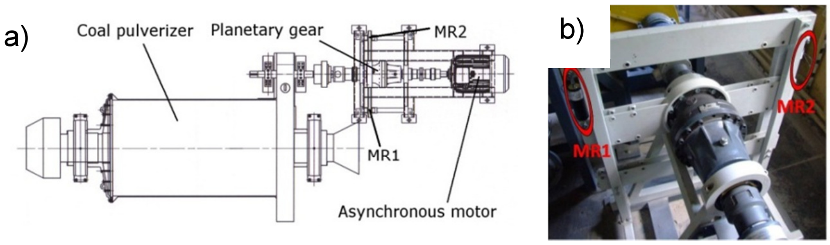

Figure 1. (a) – Scheme of the of the coal pulverizer drive system,
(b) – planetary gear support frame with two MR dampers mounted

The general purpose of the considerations is to control torsional vibrations of the power-station coal-pulverizer drive system driven by means of the asynchronous motor and the double stage planetary gear, as shown in Fig. 1a and 1b. The planetary gear housing is visco-elastically connected with the immovable foundation by means of two or four linear actuators with the magneto-rheological fluid, which is illustrated in Fig. 1b. The actuators support the gear housing at both ends of the proper reaction arm enabling it bounded rotational displacements around the drive system rotation axis. Using such suspension of the gear housing control forces generated by the linear actuators can be imposed on the drive system in the form of control torques.

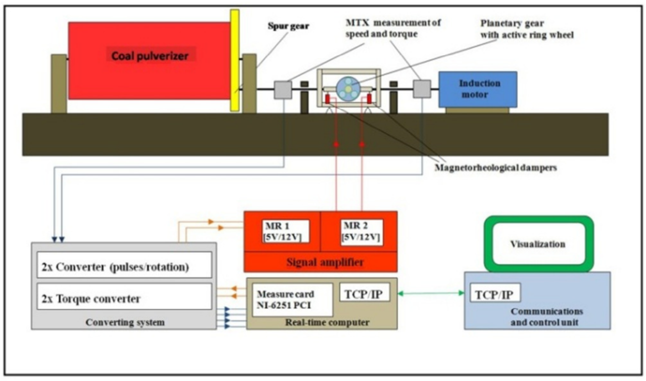

Figure 2. Measurement-control system of the coal pulverizer

In the considered drive system of the coal pulverizer power is transmitted from the asynchronous motor to the driven machine tool by means of the three elastic couplings, double-stage planetary reduction gear, the two torque-meters, electro-magnetic overload coupling and by the shaft segments. Whole stand is observed and controlled in the real-time by the use of dedicated control and data acquisition systems. This setup enables us to perform measurement of dynamic torques and rotational speed fluctuation signals in the input and output shaft, respectively. When needed, additional sensors can be added, as for example the sensor measuring the planetary gear arm position. In dedicated PC units, the real-time processors make use of recorded data, and by means of the usersupplied control algorithm, they generate control signal which is immediately applied to the linear actuators with the magneto-rheological fluid.

2. Assumptions for the mechanical models and formulation of the problem

In order to perform a theoretical investigation of the semi-active control applied for this mechanical system, a reliable and computationally efficient simulation models are required. In this paper dynamic investigations of the entire drive system are performed by means of two structural models consisting of torsionally deformable one-dimensional beam-type finite elements and rigid bodies. These are the classical finite element model and the discrete-continuous (hybrid) model. Both models are characterized by the identical structure resulting in the same division into cylindrical beam elements representing successive drive train components, which can be illustrated in common Fig. 3.

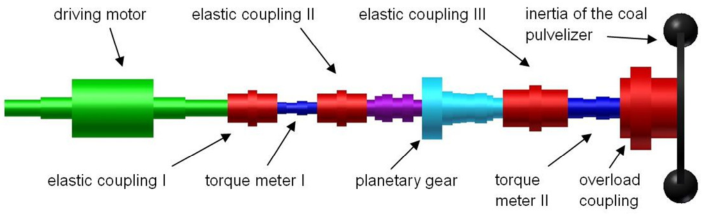

Figure 3. Mechanical model of the coal pulverizer drive system

These models are employed here for eigenvalue analyses as well as for numerical simulations of torsional vibrations of the drive train. In the hybrid model successive cylindrical segments of the stepped rotor-shaft are substituted by the cylindrical macro-elements of continuously distributed inertial-visco-elastic properties, as presented in Fig. 3. However, in the finite element model these continuous macro-elements have been discretized with a proper mesh density assuring a sufficient accuracy of results. In the proposed hybrid and FEM model of the coal pulverizer drive system inertias of the gear wheels, gear housing with the reaction arm, coupling disks and others are represented by rigid bodies attached to the appropriate macro-element extreme cross-sections, which should assure a reasonable accuracy for practical purposes. The time- and response-dependent external active and passive torques are continuously distributed along the respective macro-elements or imposed in the concentrated form on the given macro-element cross-sections.

For the assumed analogous linear finite element model the mathematical description of its motion has the classical form of a set of coupled ordinary differential equations

$$\mathbf{M}\,\ddot{\mathbf{s}}(t)+\mathbf{C}\big(C_0(t)\dot{s}(t)\big)\dot{\mathbf{s}}(t)+\mathbf{K}\,\mathbf{s}(t)=\mathbf{F}\big(t,s(t),\dot{s}(t)\big) \tag{1}$$

where: $\mathbf{s}(t)$ denotes the vector of generalized co-ordinates $s(t)$, $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are respectively the mass, damping and stiffness matrices and $\mathbf{F}$ denotes the time – and system response – dependent external excitation vector. By means of Eqs. (1) numerical simulations of the forced torsional vibrations for the passive and controlled system can be carried out. In order to determine natural frequencies and eigenvectors for the FEM model of this drive system it is necessary to reduce (1) into the form of standard eigenvalue problem. The mathematical description and solution for the mentioned hybrid model of drive system have been demonstrated in details in [2]. It is to notice here, that the dynamic responses and their control are going to be investigated in the domain of generalized co-ordinates in the case of the FEM model application and in the space of modal functions in the case of the hybrid model.

Apart from the sufficiently realistic mechanical models of the vibrating object, it is also necessary to introduce a proper mathematical model of the electric motor. In the considered case of the symmetrical three-phase asynchronous motor electric current oscillations in its windings are described by four Park's equations, which can be found e.g. in [3]. Then, the electromagnetic torque generated by such a motor can be expressed by the following formula:

$$T_{el} = \frac{3}{2} pM\left(i_{\beta}^{s} \cdot i_{d}^{r} - i_{\alpha}^{s} \cdot i_{q}^{r} \right), \tag{2}$$

where: M denotes the relative rotor-to-stator coil inductance, p is the number of pairs of the motor magnetic poles and $i_\alpha^{\,s}$, $i_\beta^{\,s}$ are the electric currents in the stator reduced to the electric field equivalent axes α and β and $i_d^{\,r}$, $i_q^{\,r}$ are the electric currents in the rotor reduced to the electric field equivalent axes d and q, see [3]. From the system of Park's equations as well as from formula (2) it follows that the coupling between the electric and the mechanical system is non-linear in character, which leads to complicated analytical description resulting in a rather harmful computer implementation. Thus, this electromechanical coupling has been realized here by means of the step-by-step numerical extrapolation technique, which for relatively small direct integration steps for motion equations derived for both applied drive system yields very effective, stable and reliable results of computer simulation.

3. Computational and experimental examples

Many experiments have been performed using the experimental test-rig, based on the real coal pulverizer drive system shown in Fig.1. In first step, the measured data was used for system parameter identification, results of which are presented in Fig. 3. The FFT analysis of the measured torque signals provided information about the system natural frequencies, see Fig. 3a. To validate the FEM and hybrid models, the modal analysis was carried out. In result, the estimated system structural spectrum was obtained, see Fig. 3b. The good correlation of numerically computed spectrum with that determined from measurement, ensures us that the proposed models sufficiently approximate the real object. Upon an identification of the system, further experiments were performed in order to investigate the worst and the best MR damper efficiency case scenarios. In the sequence, the system has been runned-ahead with several increasing levels of an operational speed. According to the fact that the excitation frequency of the coal pulverizer strictly depends on its rotational speed, the variety of load case scenarios

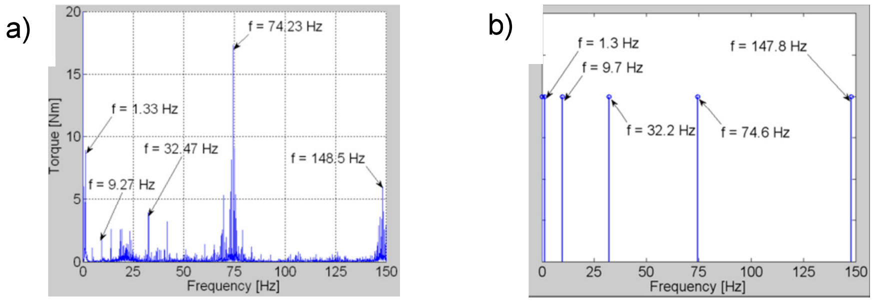

Figure 3. The spectrum: (a) – of the dynamic torque obtained from measurement, (b) – of the system obtained from the FEM model eigenanalysis

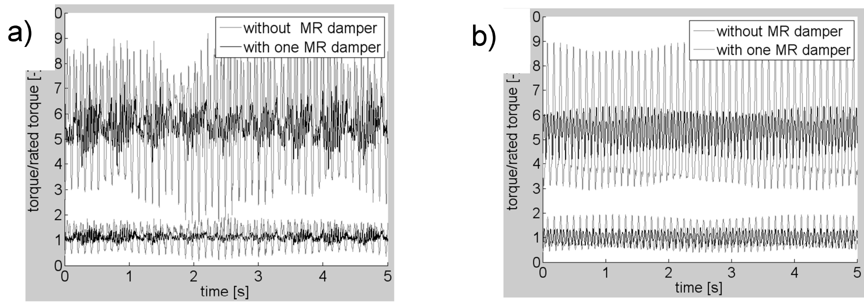

Figure 4.The input and output torque meter signals, with and without MR damper: (a) – obtained from measurement, (b) – obtained from simulation

have been analysed in this way. In Fig. 4 the following example of the MR damper efficiency scenario is presented. As one can see, in this case an application of the linear damper with the MR fluid has benefited in about 60 % measured decrease of dynamic torque amplitude reduction on the real object, Fig. 4a, and in about 65 % in the case of numerical simulation performed using the both applied theoretical models.

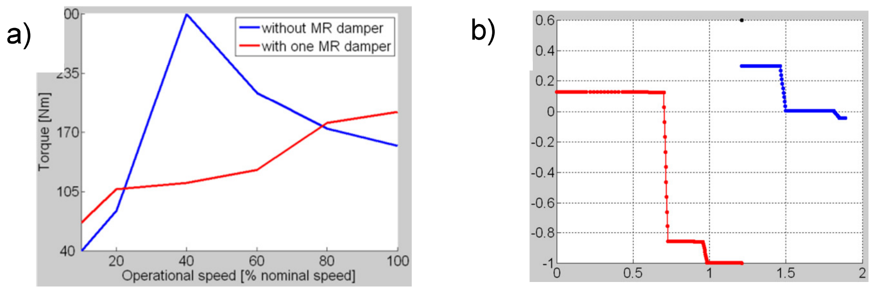

Figure 5. The averaged dynamic torque oscillation amplitude vs. the system average rotational speed (a), the second mode shape of the drive system

The next figure, i.e. Fig. 5a, presents the relationship between the level of the output shaft dynamic torque oscillation amplitudes and the system average nominal operational speed influencing the frequency of system excitation generated by the driven machine. From this figure it follows that the drive system is damped in the most efficient way in the vicinity of 40% of the motor nominal speed. At this speed the second system natural frequency f_2 = 9.7 Hz is being excited the most remarkably. Because the second mode shape shown in Fig. 5b is characterized by a significant modal displacement value at the location of the MR damper in the considered drive train, the attenuation of torsional vibrations is very efficient in this case.

4. Conclusions

In the paper a semi-active control of transient and steady-state torsional vibrations of the coal pulverizer drive system driven by the asynchronous motor and the planetary reduction gear has been performed by means of the linear dampers with the magneto-rheological fluid (MRF). Here, such dampers are able to suppress the torsional vibrations by means of mechanical energy dissipation during relative rotational motion between the planetary gear housing and the immovable foundation. As it follows from the carried out experiments and numerical simulations, such reduction results in a minimization of vibration amplitudes up to 60% in comparison with the passively damped system.

Acknowledgement

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