Mechanical Systems and Signal Processing 43 (2014) 90–102

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Adaptive control of a rotating system

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ARTICLE INFO

Article history:
Received 21 February 2013
Received in revised form
3 September 2013
Accepted 18 September 2013
Available online 11 October 2013

Keywords:
Adaptive control
Semi-active control
Vibration control
Shaft vibrations
Torsional vibrations
Magneto-rheological dampers

ABSTRACT

In the present paper, an adaptive control of structural vibrations is presented. Based on earlier research, we claim that the periodical switching on of magneto-rheological controlled dampers results in the reduction of the amplitudes of vibrations more than does their permanent actuation. This statement, when applied to a moving load problem, was mathematically proved in earlier papers. In the present paper we determine the efficiency of such a control applied to a rotating shaft. The earlier mathematical analysis allows us to propose a control strategy. A finite element simulation together with the solution of the control problem shows that the dampers should act only during a short period of the highest displacements of the structure. The same conclusion is found in experimental tests. Although high frequency control with MR dampers is less efficient than in the theoretical investigations, we have found an amplitude reduction in the range of 10–20%.

1. Introduction

Self-adaptive technologies are commonly applied to structures that carry an external load. Several advantages result from such implementations. First, the structure gains increased load carrying capacity. Second, there are lower displacements and lower fatigue, which increases the safety of the structure. Third, the control and intended action applied to certain elements of a complex system in incidental extreme cases allows reducing destructive effects. Vibration damping, amplitude reduction, and the smooth response of the structure to external loads seem to be the widest branch of engineering activity in the field of structural dynamics.

Over the last decades, adaptive control methods have proved to be attractive solutions for both small and large-scale structures. Low in power consumption, externally controlled magneto or electro-rheological dampers can efficiently reduce undesired vibrations, enabling a system to follow the desired trajectories or increasing its stability. In [1], the idea of damping a one-degree-of-freedom oscillator moving on a rugged surface was presented. The elaborated algorithm, now called “skyhook”, is commonly used in systems of semi-active control of vehicle suspension. In structural control, these methods are used for the adaptive suspension of a moving oscillator in [2,3]. In some recent papers, variable dampers are incorporated for seismic isolation, for example in [4,5]. A theoretical approach to the problem of the controlled damping of beam vibration, based on the method of optimal Lyapunov functions, is presented in [6]. In [7], the authors propose to control both parameters: stiffness and damping. The control function leads to the maximum dissipation of energy. Generally, a reduction of amplitude needs to be achieved. The problem of reducing beam vibrations using active control methods is also widely considered in [8]. An analysis in the frequency domain allowed the authors to reduce the maximum

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http://dx.doi.org/10.1016/j.ymssp.2013.09.006

amplitudes. An actively controlled string system was considered in [9]. Other interesting results in structural control are presented in [10–12]. Active methods are in general more effective than semi-active ones, but the power consumption of the latter is significantly lower. The idea of a magneto-rheological fluid damper for rotor applications was presented in [13–15]. Experimental results were given. The same concept was developed in [16].

Direct control theory and the theory of inverse problems have stimulated the development of health monitoring of structures: identification of the dynamic load [17,18] and simultaneous identification of the load and any damage to a structure [19].

A good example of the control of vibrations under a load is described in [20], which presented a method for computing the response induced by a load traveling over a 1D elastic continuum supported by a set of semi-active viscous dampers. An adaptive open loop control strategy was proposed. The damping functions were taken to be piecewise constant. The control strategy was suboptimal, but it outperforms the passive case. Numerical results were presented for the cases of a string and a Bernoulli–Euler beam. In [21], two elastic beams are coupled by a set of controlled dampers. The relative velocity of the spans provides an opportunity for efficient control via adaptive suspension. As a result, bang–bang controls are taken into account. The controlled system outperforms passive solutions over a wide range.

Torsional vibrations are undesirable in drive systems, turbines, or vehicles. In practice, the detection and elimination of vibrations are difficult. The machine should be re-designed or at least the operation in the critical range of parameters should be reduced to a minimum. One of the few works devoted to a rotor mechanical model [22] presents two different control schemes: the on-off scheme and the feedback linearization scheme. It is shown that a magneto-rheological damper can provide sufficient damping for ground resonance stabilization.

In the present paper, we consider the influence of one magneto-rheological damper on the vibrations of a shaft. The advantage of the semi-active approach is evident when we consider the energy consumed by the dampers. First we give a closed solution of the problem reduced to the first mode of vibrations. This will give us insight into the problem and will allow exploring the solution analytically. Then, more accurate semi-analytical solutions of the problem will be presented. The control problem will be formulated and its solution will be given. The IPopt package will be applied for multi variable optimization. Finally the experiment verifies and demonstrates the efficiency of our approach.

The idea of rotatory damping of a shaft, which is analyzed below, was presented in [23,24].

2. Mathematical model

The observation of vibrations over a long period of time can only be performed stochastically, i.e., assuming that the amplitudes achieve their extremal values not in accordance with a smooth function of the initial conditions and material parameters. Therefore, the deterministic way of investigation forces us to calculate analytically at the first stage. This will facilitate the estimation of the sensitivity of the structure to selected parameters.

The real structure under consideration is here simplified to that depicted in Fig. 1. The model of the shaft, however, will first be reduced to the shaft of a uniform cross section, without concentrated masses placed on it. Only in such a case can we successfully carry out the mathematical analysis. First we will consider the problem with an excitation applied to the point A and with a single damper placed at the point B (Fig. 2).

We consider the hyperbolic differential equation (1) which describes the motion of the rotating shaft. The second equation (2) describes the motion of the damper. They are coupled at the point B:

$$-GI\frac{\partial^2\varphi}{\partial x^2}+\rho I\frac{\partial^2\varphi}{\partial t^2}+\delta(x-x_B)c\left(\frac{\partial\varphi}{\partial t}-\frac{\partial\vartheta}{\partial t}\right)=\delta(x-x_A)f(t), \tag{1}$$

$$I_d\frac{\mathrm{d}^2\vartheta}{\mathrm{d}t^2}+c\left(\frac{\mathrm{d}\vartheta}{\mathrm{d}t}-\frac{\mathrm{d}\varphi}{\mathrm{d}t}\right)=0. \tag{2}$$

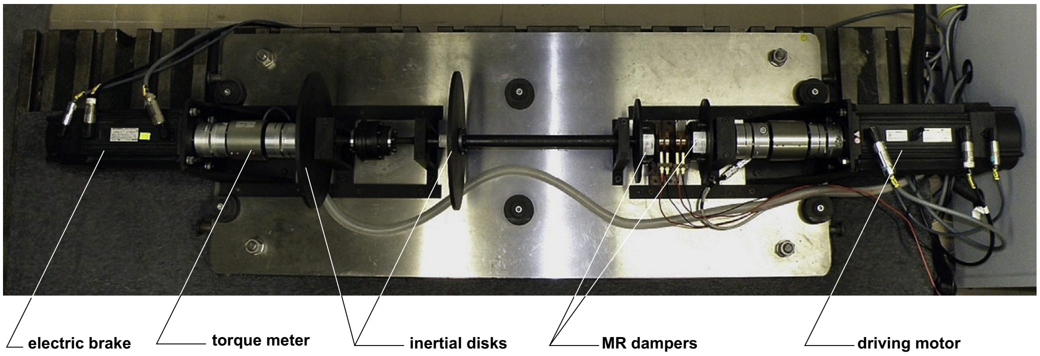

Fig. 1. The test stand.