Chinese Journal of Aeronautics (2014) **27**(1), 182–188

CSAA

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

JOURNAL OF AERONAUTICS

Two-stage open-loop velocity compensating method applied to multi-mass elastic transmission system

Zhang Deli *, Yang Haiqiang, An Luling

College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Received 7 July 2013; revised 28 August 2013; accepted 4 November 2013
Available online 19 December 2013

KEYWORDS

Fuzzy control;
Mechatronics;
Multi-mass system;
Open-loop control;
Vibration control

Abstract In this paper, a novel vibration-suppression open-loop control method for multi-mass system is proposed, which uses two-stage velocity compensating algorithm and fuzzy I + P controller. This compensating method is based on model-based control theory in order to provide a damping effect on the system mechanical part. The mathematical model of multi-mass system is built and reduced to estimate the velocities of masses. The velocity difference between adjacent masses is calculated dynamically. A 3-mass system is regarded as the composition of two 2-mass systems in order to realize the two-stage compensating algorithm. Instead of using a typical PI controller in the velocity compensating loop, a fuzzy I + P controller is designed and its input variables are decided according to their impact on the system, which is different from the conventional fuzzy PID controller designing rules. Simulations and experimental results show that the proposed velocity compensating method is effective in suppressing vibration on a 3-mass system and it has a better performance when the designed fuzzy I + P controller is utilized in the control system.

1. Introduction

Complicated vibration problem occurs frequently in mechanical transmission systems because of the insufficient torsional stiffness of the mechanical driving parts. This kind of flexible multi-mass transmission system can be found in many industrial applications, such as flexible joints of articulated robots, drive train of a wind energy plant, steel rolling mills, textile drives, etc. Recently, control systems that applied to mechanical driving devices have been increasingly requiring that the whole system has a fast-responding and high-accuracy performance, which can result in easily exciting vibrations in the mechanical system.

A lot of controlling methods have been proposed to reduce the vibration of elastic transmission systems. Most of the investigations are focused on the simplest representation of flexible mechanical driving system, i.e., a 2-mass system.[1–10] Some fundamental limitations in the 2-mass system have been discussed and analyzed to confirm the limiting performance of controllers applied to 2-mass systems.[1] A systematic analysis of controller design principles and a comparative study of control structures for the 2-mass system have been carried out. The combination of control structure with PI controller supported by different additional feedbacks was presented.[2] In order to improve the practical performance of the flexible transmission system, more advanced and complicated control

* Corresponding author. Tel.: +86 25 84891678.
E-mail address: nuaazdl@126.com (D. Zhang).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

1000-9361
http://dx.doi.org/10.1016/j.cja.2013.12.013

algorithm are utilized. Kalman filters are applied to the high-performance drive system with elastic coupling.[3] Feed-forward neural networks are used to estimate the non-measurable state variables of 2-mass system, such as the torsional torque and the load machine speed.[4] A fuzzy controller and a gray estimator are applied to a non-linear 2-mass system and the robustness of the control system are tested.[5] To improve control performance, disturbance observers (DOB) are implemented in 2-mass control systems.[6–8] It is possible that these controllers will have satisfactory performance only when the mechanical system is allowed to be simplified as a 2-mass system.

However, in more complicated transmission systems, 2-mass system model cannot accurately present the vibration characteristics of the objective system. In order to solve this problem, multi-mass models of different flexible drive trains have been built and analyzed.[11–13] Six different flexible drive train models of wind turbine (i.e. 6-mass, 4-mass, 3-mass I, 3-mass II, 2-mass and 1-mass models) are built and their influences on the transient performances of wind turbine are examined.[11] An identification method based on the linearized and weighted total least squares (LWTLS) method is presented to derive the transfer function for 3-mass and 4-mass systems without any prior knowledge of resonance characteristics and time delay.[12] Different kinds of Control ling methods used for vibration suppression in multi-mass systems have been investigated.[14–21] The least squares-estimation (LS-estimation) method with ARMAX model and fast Fourier transformation (FFT) are proposed to estimate the mechanical parameters of a 3-mass system.[14] The identification of an industrial robot, which is regarded as a 3-mass system, is accomplished in the closed position control loop and is carried out by moving one axis at a time only.[15] The artificial pseudorandom binary test signal (PRBS) is utilized for stimulating multi-mass systems. From the measurement signals, the frequency response of the mechanical system can be calculated.[16–19] A funnel controller, which is a time-varying control method, is designed for controlling the non-linear time-varying multi-mass flexible system.[20] A digital modified-IPD regulator for speed loop is proposed to suppress vibrations of the load side inertia of 3-mass system and Particle Swarm Optimization (PSO) is used for the determination of the controller parameters.[21] These control methods are either complicated to realize in practical applications or only effective in specified environment.

In this paper, a more practical two-stage compensating method applied to velocity loop is proposed for vibration suppression of multi-mass elastic transmission system. This compensating method is applicable in industrial situations where no intense disturbance occurs, such as articulated carrying robot, welding robot, etc. It is used to suppress vibrations caused by sudden change of velocity such as sudden starting and stopping of machines. In the open-loop control system, the mathematical model of the system is built to estimate the velocities of masses. The estimated velocity difference that needs to be compensated is calculated dynamically according to the system model. After being regulated by a PI controller, the velocity difference is finally converted to the motor input to suppress the vibration of the whole mechanical system. In order to achieve better vibration suppression effect, a fuzzy I + P controller is utilized in the general compensating stage instead of using a conventional PI controller. The parameter of integral part is optimized dynamically according to fuzzy rules during the regulating process of the system. Different from the conventional design of fuzzy PID controller, the impact of different input variables of K_i fuzzy tuner on the whole system is analyzed and the conventional input variable d$e(t)$ is replaced by more relevant variable. Comparative simulations and experiments are carried out to verify the effectiveness of the proposed compensating method.

2. Two-stage open-loop compensating method

2.1. System description

The structure of a 3-mass elastic transmission system can be expressed as Fig. 1. Mass 1 is rigidly connected to motor, which provides rotating energy for the whole system. The connection between Mass 1 and Mass 2 is flexible, so is the connection between Mass 2 and Mass 3. When the motor starts to move at a constant speed, Mass 2 and Mass 3 will both vibrate severely for a long time before they can rotate stably.

2.2. Two-stage compensating method

When the whole system is stable, the velocity difference between adjacent rotating masses should be zero. So the final goal of the system controller is to make adjacent masses rotate at the same speed. The velocity difference is chosen as the compensating quantity.

In the two-stage compensating method, the 3-mass flexible system is regarded as the composition of two 2-mass systems. Mass 2 and Mass 3 together forms a 2-mass system, which is also regarded as a subsystem. Mass 1 and subsystem, which is composed of Mass 2 and Mass 3, is regarded as another 2-mass system (Fig. 2). The velocity difference $\Delta\omega_{23}$ between Mass 2 and Mass 3 is calculated dynamically and it is regarded as the velocity that needs to be compensated for subsystem. After being regulated by a P controller, $\Delta\omega'_{23}$ is added to the velocity of Mass 2 ω_2. Then a new velocity of Mass 2 ω'_2, which includes two parts: velocity compensation for the subsystem $\Delta\omega'_{23}$ and velocity of Mass 2 ω_2, is achieved. Then the velocity difference $\Delta\omega_{12}$ between Mass 1 and subsystem is calculated dynamically. $\Delta\omega_{12}$ is also the velocity that needs to be compensated for the whole mechanical system. After being regulated by a PI controller, the final compensating velocity $\Delta\ \omega_f$ is negatively added to the speed command of motor ω_{cmd} to realize the vibration suppression for mechanical part. The output

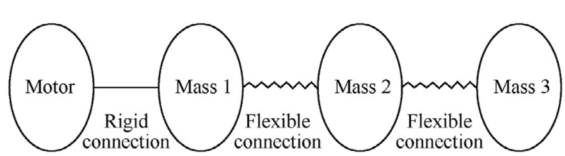

Fig. 1 3-mass elastic transmission system.