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A novel vibration measurement and active control method for a hinged flexible two-connected piezoelectric plate

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ABSTRACT

A novel non-contact vibration measurement method using binocular vision sensors is proposed for piezoelectric flexible hinged plate. Decoupling methods of the bending and torsional low frequency vibration on measurement and driving control are investigated, using binocular vision sensors and piezoelectric actuators. A radial basis function neural network controller (RBFNNC) is designed to suppress both the larger and the smaller amplitude vibrations. To verify the non-contact measurement method and the designed controller, an experimental setup of the flexible hinged plate with binocular vision is constructed. Experiments on vibration measurement and control are conducted by using binocular vision sensors and the designed RBFNNC controllers, compared with the classical proportional and derivative (PD) control algorithm. The experimental measurement results demonstrate that the binocular vision sensors can detect the low-frequency bending and torsional vibration effectively. Furthermore, the designed RBF can suppress the bending vibration more quickly than the designed PD controller owing to the adjustment of the RBF control, especially for the small amplitude residual vibrations.

1. Introduction

A solar array system is one of the important components of spacecrafts. The solar array system is in folded state during spacecraft launch and ascent. After the spacecraft and launch vehicle are separated and the spacecraft is turned into the free flying orbit, the solar array system will be deployed by driving mechanism [1]. The large-scale flexible solar panel structures consist of several plates which are connected together by hinges. Due to the influence of orbit control or external disturbances, the vibration problem will be inevitably caused during operation. The vibration will last a long time without active control in space enviornment. Unexpected vibration will seriously affect the normal operation of spacecraft equipment, reduce its accuracy, accelerate structural fatigue damage, and even cause the tumble of the spacecraft [2]. Therefore, research on vibration measurement and suppression of flexible hinged plate structures is realistic and prospective.

For vibration testing, sensors can be divided into contact type and noncontact type. Contact type sensors include piezoelectric patches (PZT, lead zirconate titanate), accelerometers, etc. PZT as a kind of smart material was effectively implemented to control the mechanical vibration of flexible structures [3]. Accelerometers are by far the most traditional and

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widely used sensors employed in modal testing due to broad band. However, the effects of mass-loading can corrupt a measurement, especially at higher frequency ranges or for lightweight structures. Furthermore, accelerometers typically measure motion at a limited number of discrete points [4].

Non-contact type sensors include vision camera, laser displacement sensor, scanning laser vibrometer, etc. Laser displacement sensors can measure motion at a limited number of discrete points, and each point needs a laser displacement sensor. Image-based stereo-photogrammetry techniques provide additional measurement capabilities for high-displacement and low-frequency vibrations, typically difficult to be measured with accelerometers and laser vibrometers. Furthermore, it can measure many points without mass-loading [4]. As a non-contact method, significant advantages of the noncontact digital video cameras are relatively low-cost, agile, ease of operation, high spatial resolution and flexibility to extract structural displacement responses at multiple points, a non-contact, global measurement technique [5]. Photogrammetric methods are particularly useful when the object to be measured is inaccessible or difficult to access, when the object moves and deforms, and when its contour and surface information is required [6].

Video camera based measurements have been successfully used for vibration measurements and modal analysis, based on techniques such as the digital image correlation (DIC) and the point-tracking [7]. Digital video cameras vibration measurement technology and the 3-dimensional point-tracking techniques have been used widely [8,9]. The photogrammetry technique is an image based measurement system and uses displacements of the points or surfaces on a structure to monitor the dynamics of the structure. Photogrammetry provides non-contacting full-field measurement capabilities and can be an alternative to the conventional point-wise measurement approaches [10].

Video camera based measurements have been used for vibration measurement of various types of structures successfully, such as civil engineering structures, helicopter blade beam structures, and bridge dynamic response displacements [11–13]. Avitable et al. [14] presented a method to measure the structural vibration using machine vision. Teyssieux et al. [15] uses a CCD camera to obtain the in-plane vibration displacement of a cantilever beam. Wang et al. [16] investigated a non-contact measurement method by using vision sensors, and they studied the fuzzy image by employing the method of image moment. Dubus et al. [17,18] investigated the relationship between the feature points of multiple images to estimate the vibration signal of the of a flexible arm's tip.

As for measurement on flexible plate structures, Purohit et al. [19] conducted experimental investigation on flow induced vibration of an externally excited flexible plate. A laser vibrometer, pressure microphone and a high-speed camera are employed to measure the plate vibration, pressure signal, and instantaneous images of the plate motion, respectively. Sabatini et al. [20] investigated an image-based technique for the vibrations data acquisition. In the experiments, the camera was used to identify the eigenfrequencies of the vibrating structure, and aluminum thin plates simulate very flexible solar panels.

The intrinsic parameters of a camera should be calibrated before vision measurement. Zhang [21] proposed a technique to easily calibrate a camera. It only requires the camera to observe a planar pattern shown at a few different orientations. The extrinsic parameters for the binocular vision system should also be calibrated. The resolution of CCD cameras may be not adequate, or not fast enough frame rate, which resulted in long processing time for the images, thus, significant lag and low update rates will be caused [22]. Therefore, the important problem of vision sensing is the delay between image capturing and image processing. In addition, visual or optical devices require a free line of sight between object and camera. To overcome these problems, control algorithms should be investigated to compensate for time delay and improve the control performance for vision-based control.

Obtaining the model of the system is the premise of the design and implementation of the model based controller. Among the modeling methods of the flexible structure, finite element method (FEM) is one of the most widely used methods for distributed parameter system. The solar panels were simplified as a single flexible plate, and the effect of the connecting hinges were neglected in the most previous works [23]. Xu and Li [24] obtained the model of the solar panel by using FEM, neglecting the effect of the connecting hinges. Zhang et al. [25] used 8-node Mindlin plate element and virtual work principle to obtain the dynamic equations of a piezoelectric cantilever plate.

The control algorithms are vital for the control performance of the controlled objects. The design of controller must be ensured that the control system has a certain stability, adaptability and autonomy. With the development of control theory, a large number of active vibration control algorithms are investigated and utilized. To improve the control performance, intelligence algorithms have been employed, such as fuzzy control [26] and artificial neural networks algorithm. Fei and Zhou [27] proposed a robust adaptive control strategy using a fuzzy compensator for MEMS triaxial gyroscope, which has system nonlinearities, including model uncertainties and external disturbances. Artificial neural networks have been applied to control complex and nonlinear systems by choosing neural network structures and training the weights properly.

A radial basis function neural network (RBF-NN) has many attractive features such as the ability of non-linear mapping and the ability of learning, as well as the ability to globally stabilize [28]. A RBF-NN is employed to approximate the nonlinearities and uncertainties. Fei and Ding [29] used RBF-NN in a class of time varying system in presence of uncertainties and external disturbance. A fully tuned RBF neural network is presented for a general class of strict-feedback nonlinear systems [30]. Fang et al. [31] combined sliding mode control and RBF neural network control algorithms for active power filter. For a class of nonlinear dynamic systems, Fei and Lu [32] proposed an adaptive sliding mode control system using a double loop recurrent neural network (DLRNN) structure. Abdeljaber et al. [33] introduced a new intelligent neural network controller to mitigate the vibration response of flexible cantilever plates by using the piezoelectric sensor/actuator pairs.