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Fuzzy control of an electrodynamic shaker for automotive and aerospace vibration testing

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ABSTRACT

A fuzzy logic based digital time domain sinusoidal acceleration waveform amplitude controller for an electrodynamic shaker is presented. The purpose of Fuzzy Logic Control (FLC) is to reproduce a predefined sinusoidal acceleration amplitude profile (in amplitude, frequency and time) at the shaker table. Sinusoidal vibration profiles (sine and logarithmic sine sweep) are considered for a controlled vibration generation in typical automotive and aerospace testing. The difficulty in sine sweep testing is that the non-rigid load dynamics are unknown and it can severely modify the shaker's performance during sweep test. Since a logarithmic frequency sweep is normally used, a controller needs to be robust to un-modeled dynamics and also fast enough to hold the desired acceleration amplitude within predefined limits throughout the sweep test. The controller structure is developed based on the usual power amplifier technology. The control action is implemented on a waveform-by-waveform basis and a FLC is developed in the LabVIEW environment on a PXI platform for real time control of the shaker. To attenuate the shaker suspension mode resonance a compensator based on electromechanical model of the shaker is designed and cascaded to FLC. The shaker model, suspension mode compensator design, FLC synthesis and experimental implementation results are presented in this paper.

1. Introduction

Vibration is one of the most classical phenomena and it has attracted the minds of great scientists' right from the days of Sir Isaac Newton. A mechanical vibration in particular is used to study the effects of vibration in structures and materials in wide variety of applications. Generally, the purpose is to simulate the environment where the Device Under Test (DUT) is used in service and is then used to investigate if it will survive to the actual usage service conditions. These applications mainly include stimulus response analysis, reliability testing, vibration sweep testing and resonance study. Vibration testing refers to subjecting a device to some predefined profile of mechanical vibrations in terms of amplitude and frequency. Several industries like defense, space, railways, airways and embedded hardware manufacturing, during critical phase of testing of their products, require vibration tests for precisely defined profiles. In general there is always a great demand for increasing the reliability of devices making use of critical components. This is accomplished by intensive vibration tests because this is the main phenomenon responsible for the durability and serviceability study of various devices. In fact vibration tests have become one of the essential and critical tests for all the test and measurement systems. Vibration testing also plays a major role in identifying faults in the machineries and in the prevention of failures leading to the mechanism of fault diagnostics (De Silva, 2000; McConnell, 1995; Tustin, 2005).

Sinusoid vibration testing is very important in the engineering development to search the product resonances and to determine the fatigue life. In the most common form, sine testing involves a logarithmic frequency sweep holding the specified acceleration magnitude at the base of the DUT. By sweeping the frequency in either direction in the range of interest according to predefined profile, adequate test reliability is attained. A PC based modern vibration equipment normally used to execute close loop sine testing comprises of an electrodynamic shaker, a power amplifier and an acceleration measurement, controlling and monitoring system as shown in Fig. 1. The vibration exciter transforms the electrical energy supplied to it into the physical movements. The interface to the PC is twofold. First, it is used for measurement of the generated vibration and second, it generates the base control signal to be fed to the power amplifier. In the usual configuration, DUT is mounted to the shakers' table along with an accelerometer used to measure the response acceleration. This feedback allows controlling the input excitation signal so as to achieve the desired reference profile in acceleration magnitude, frequency and time. The control platform excites the shaker using an appropriate power amplifier by generating the required drive signal (Tustin, 2005).

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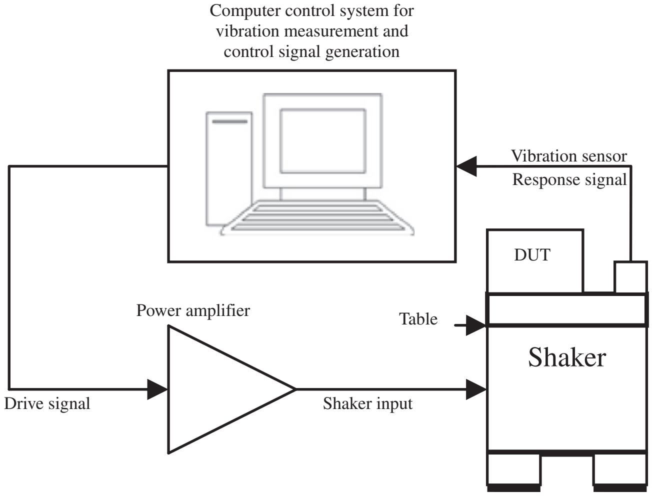

Fig. 1. Vibration testing system components.

1.1. Brief bibliographical review of electrodynamic shaker control mechanisms

This section gives a brief survey of the recent work done in this area. The control technique of typical industrial shaker controllers for sine testing is essentially a frequency domain approach, usually referred to as transfer function equalisation, before starting the test; the controller outputs a small broadband random excitation signal to the shaker. Based on the measured response, the inverse transfer function of the vibration generation process is estimated. This information is then used to generate the control signal so as to compensate the estimated process dynamics. During the test execution, the controller is required to monitor and constantly update the inverse transfer function as needed (LDS Test & Measurement, 2005). In this scheme no prior very specific structural parameters of the shaker, or of power amplifier, are required. As reported in (Keller, 2002), this technique relies on the use of very selective tracking filters to attenuate any frequency rather than the controlled one, which improves the measurement accuracy and keeps the focus in magnitude control instead of root mean square (RMS). Most of the current industrial shaker controllers have evolved from platforms used to build dynamic signal analysers, so that the high signal-to-noise ratio and the wide dynamic range of these instruments are also featured for shaker control. However, despite all the desirable characteristics, the nature of the transfer function equalisation technique and its implementation require relatively long processing time to manipulate large blocks of data samples. Consequently, for sine testing, in particular, the resulting delay in updating the drive signal in response to changes in the input acceleration makes it difficult to achieve stability and good reference tracking under the effects of high Q resonances of non-rigid test loads, especially during the frequency sweep.

Baoliang et al. proposed a Fast Fourier Transform (FFT) based variable sampling rate method for sine magnitude control. According to simulation results, this approach has improved the amplitude identification accuracy without using tracking filters, which significantly increases the controller response and precision during the frequency sweep. However verification and validation of proposed method on a physical system was not presented (Baoliang & Xia, 2003).

Chen et al. presented an analog acceleration amplitude controller for an inverter-fed shaker using conventional PI control mechanism for sinusoid excitation based on time domain feedback. Reference and disturbance feedforward control were proposed and further developed for random tests. Robustness to parameter variations were demonstrated experimentally. This scheme specifies as drive signal not the shaker excitation voltage or current, but an internal state of an amplifier, which strongly prevents its application to the usual power amplifier technology in vibration testing. The settling time of the proposed control logic is reported as 1 s. Furthermore, the performance of sine sweep test as required by the industry is not investigated and reported for desired sweep rate and wider frequency range (Chen & Liaw, 1999; Liaw, Yu, & Chen, 2002).

Uchiyama et al. achieved the electrodynamic shaker robust control by means of two controllers. The two control variables are acceleration and displacement of the shaker's table. Two control variables are used in order to control a broad frequency band. Frequencies where the response signals are larger than the noise, the acceleration control is employed. For lower frequencies the displacement control mechanism is employed. Both of these methods are coupled in series. Finally the control mechanism was tested on an electrodynamic shaker and some comparisons were drawn. They further extended this concept by adding an adaptive filter to the two degrees of freedom controller. The adaptive filter based on the H_∞ filtering mechanism is employed. Performance of the developed double control loop logic on the resonant load testing was not reported (Fujita & Uchiyama, 2006; Uchiyama, Mukai, & Fujita, 2009).

Flora et al. researched the digital acceleration controllers for sinusoidal vibration tests using a switching-mode AC power source (ACPS) for an electrodynamic shaker. The proposed scheme made use of two control loops in interaction. One loop was used for the acceleration regulation. The other loop was used for the ACPS voltage output control. Robust model reference adaptive algorithm was used to reduce the effects caused by the variations on the system and to reduce the harmonic and resonant vibrations on the test piece. The experimental results have shown that the proposed system is able to attain a good performance in relatively narrow frequency bands from 20 Hz to 200 Hz and the effect of load resonance was not examined (Flora & Gründling, 2006). In a recent work, they have also researched the digital acceleration controller in time domain for sine vibration testing on electrodynamic shaker. Cascade of compensators were used to attenuate the shakers' structural resonances. Acceleration control was implemented using a reference tracking compensator. They implemented sample-by-sample basis control mechanism for faster drive signal correction. The controller structure was developed based on the usual vibration testing power amplifier technology in the automotive range. Detailed procedure for shaker modeling and control logic development was presented and supported by the experimental results. An acceleration tracking error of 10% was reported for reference tracking in sine sweep test in automotive range of frequencies. The controller performed well for rigid loads and had limitation to dynamic test loads. No specific method or approach for reference tracking controller tuning was mentioned (Flora & Gründling, 2008).

Some other studies reported in the literature are on the modeling and controller design of the electrodynamic shaker systems. Fair et al. carried out the analysis and design of shaker system. They studied the electrical features of the moving coil vibration generators (Fair & Bolton, 1993). Darie et al. have theoretically researched computational aspects of electrodynamic system for its controllability, stability and observability and proposed inclusion of the device in automatic control systems. No specific controller was proposed, implemented and experimentally verified (Darie, Colosi, Vadan, & Balan, 1994). Macdonald et al. presented analysis and control of a moving coil electrodynamic shaker. They developed a model and studied the controller design by pole placements. The model was validated to the actual physical system