Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the detailed literature reviews conducted on the complex periodic waveform measurement and presentation on the oscilloscope and acceleration control for vibration testing on an electrodynamic shaker system. As the thesis is organized in two major sections the survey is also conducted accordingly. Initially, functioning of an oscilloscope and triggering mechanism used are explained. The limitations of the existing/conventional triggering mechanisms are reviewed and analyzed. For the second component, detailed literature review on closed loop electrodynamic shaker control mechanisms was conducted and has been presented. In both the cases limitations of the existing techniques are evaluated and highlighted for the relevance and usefulness of the problem taken in this research.

2.2 Waveform measurement and presentation

This section discusses various triggering methods and their limitations for measurement and presentation of complex periodic waveforms. Oscilloscopes are used for the live graphical presentation and basic measurement of the electrical signal waveforms [Gregory, 1981; XYZ of Oscilloscope]. Oscilloscope presents a live signal as visually stationary on its display by the way of displaying integral number of complete waveforms repeatedly with the help of appropriate triggering mechanisms. For continuous and stable display on the oscilloscope, the horizontal sweep time must coincide with the input waveform time period or to its integral multiples. This instrument makes use of level triggering in which the amplitude levels (zero crossings) are sufficient to estimate the waveform time period [Gregory, 1981; Yang & Lizhong, 2005]. In the recent years, the high-speed digital design and complex modulation methods have put a vast challenge for the
Figure 2.1: Frequency varying damp sine waveform.

Conventional methods of period extraction in time domain, like amplitude levels or zero crossing have limitations for dynamic signals. With the advent of high speed and deterministic real
time micro-computing mechanisms, relatively complex and advanced algorithms for time period estimation and oscilloscope triggering can now be realized. Simple, fast and robust algorithm catering to wide varieties of the waveform types form the essential features for a new candidate method for time period extraction and real time trigger generation for oscilloscope. To extract the period of complex waveforms in time domain, the waveforms are subjected to self similarity check by the way of time shifting and comparing it with the pre-stored reference [Khan, Agarwala, Shahani & Alam, 2007]. Processing time series data for similarity checks has been dealt as ‘similarity measurement’ in the literature. Similarity measures also finds its basis in machine learning, data mining, pattern recognition, signal processing, artificial intelligence and multi-agents system fields. The choice of the similarity measure method determines the effectiveness of the algorithm in solving the specific problem making it an active area of research [Agrawal, Sawney & Shim, 1995; Das, Gunopoulos & Mannila, 1997].

In recent years, there has been a great deal of research in the similarity search area. There are several different similarity measurements that have been proposed in the literature as well as several algorithms for the efficient retrieval of the similarities. Euclidean Distance (ED) model is the simplest and classical method for similarity measure between two sequences. Two sequences are considered similar, if the ED between them is less than a pre-defined threshold. The major shortcoming in ED model is its inability to handle the outliers and it is also very sensitive to distortions [Jia-Cheng, Yin, Hong & Qi-Lun, 2004; Toshniwal & Joshi, 2005; Boudraa, Cexus, Christophe & Brunagel, 2008].

Hamming distance is another simple and efficient similarity measure, but, since it is designed to deal with binary vectors, it cannot be applied to problems that use real-valued vectors. Fuzzy Hamming Distance (FHD) is another variant of hamming distance, designed to operate on real-valued vectors and maintain the same meaning as the hamming distance [Ralescu, 2003]. FHD technique has been employed as similarity measure in several experiments as basis for content based image retrieval system etc. The drawback of the FHD method is the overhead incurred in pre
and post processing of the data [Xuelong, Yang & Gensbeng, 2007]. In [Khan, Agarwala, Shahani, & Alam, 2007], a variant of Hamming distance called Weighted Hamming Distance (WHD) method was proposed as similarity measure and was utilized on Field Programmable Gate Arrays (FPGA) to trigger oscilloscope for capturing the complex waveforms. The number of time shifts between two successive minima (ideally zero when no noise is present) in the WHD output waveform gives the waveform time period. This technique is suitable for binary vectors. DAQ card based systems deal with the real values and hence suffer heavy data conversion time. The data processing in binary format consumes lots of processor’s time, making the WHD method less efficient for trigger generation on a microprocessor based system.

Frequency domain similarity measures, including the discrete Fourier transform and wavelets are also reported in the literature [Rafiei & Mendelzon, 1998; Chan & Fu, 1999; Struzik & Siebes, 1999; Popivanov & Miller, 2002]. For real time triggering and period extraction applications, these are not preferred as they demand intensive computing. The one of the main aims of this work is to study and investigate new methods for complex waveform period estimation and live presentation and hence advanced oscilloscope triggering.

2.3 Electrodynamic shaker control

This section presents a survey of the recent work done in the area of electrodynamic shaker control. 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 process dynamics. During the test execution, the controller is required to monitor and constantly update the inverse transfer function as needed [LDS Test and 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 of 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 tests.

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 test. However, the verification and validation of proposed method on a physical system was not presented [Baoliang, 2003].

Chen et al. presented an analog acceleration amplitude controller for an inverter-fed shaker using conventional Proportional-Integral (PI) control mechanism for sinusoid excitation based on time domain feedback. The reference and disturbance feed-forward control were proposed and further developed for random tests. The 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 utilized is very large of the order of 1s. 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 were acceleration and displacement of the shaker’s table. Two control variables are used in order to control a broad frequency band. For frequencies, where the response signals are larger than the noise, the acceleration control is used. For lower frequencies the displacement control mechanism is utilized. 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 2DOF controller. The adaptive filter based on the \( H_\infty \) 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. The 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 200Hz and the effect of load resonance was not examined [Flora & Grundling, 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 shaker structural resonances. The 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 of shaker modeling and control logic development were 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 & Grundling, 2008].

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]. The shaker is claimed to be a nonlinear system on account of the eddy currents, friction, heating effects, deep frequency dependencies of the resistance and the inductance, suspension system, the test load dynamics etc.

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 with bare table. No results on any type of load testing and sine sweep profile were reported [Macdonald, Green & Williams, 1993].

The other works on analysis and design of electromagnetic moving coil vibration generators are also reported [Lang, 1997; Lang & Snyder, 2001]. Shaker design and associated complexities are presented in detail. This work is very general and deals with the features of the electrodynamic systems.

2.4 Literature survey concluding remarks on shaker control

The literature survey on the electrodynamic shaker control conducted above clearly indicates that the shaker system has complex dynamics and there are certain un-modeled
parameters and nonlinearities inherent in terms of the damping, suspension system and friction. There exist deep frequency dependencies on the shaker’s armature electrical parameters owing to the wide-frequency excitation. Additionally, test load dynamics changes the mechanical parameters of the shaker, especially the test mass. Shaker’s spring-mass suspension resonances and modeling errors equally contribute to make almost unusual open loop operation. Furthermore, very limited types of vibration controllers have been studied and actually implemented for vibration control on the shaker systems. The shaker system and its controllers have been mainly developed in the industrial domain. This is one of the reasons that the intelligent controllers based on fuzzy logic or neural network, studied by the academicians for several years and by now established to some extent, have not been tried out on the complex system like vibration exciters. The most recent and efficient, but relatively complex algorithms, like Fuzzy Logic Control (FLC) are yet unexplored on the shakers. Good amount of literature is available on these new technologies now and they have gone through many technical innovations in the past three decades. Additionally, in contrast to the industrial process control technologies, where large varieties of controllers have been studied and implemented, the work available in shaker control domain is very-very limited. Bridging of such technical gap is one of the main aims of the proposed research.

Classical Proportional-Integral-Derivative (PID) controller remains an important control tool due to its past record of success, wide availability and simplicity in design and use. These reasons enforce one another, thereby ensuring that the more general framework of digital control with higher order controllers has not really been able to displace PID control. For example, it has been reported that more than 90% of control loops in Japanese industry are of PID type [Yamamoto & Hasimoto, 1991; Astrom & Hagglund, 2001]. This is also believed to be true elsewhere [Swallow, 1991]. Furthermore, it has set guidelines for tuning and has witnessed a long journey in its developments over the years [Chen, 1996; Ang, Chong & Li, 2005]. PID controllers continually attract attention, from both the academic as well as the industrial researchers, with many new recent studies being published [Luo, 1998; Grimble, 2001; Liu, et al., 2001; Silva, et al., 2002; Tokuda &
Yamamoto, 2002; Zheng, 2002]. As mentioned above, on electrodynamic shaker a classical PI acceleration amplitude analog controller is implemented by Chen et al. [Chen, 1999]. It may be noted that PID control law is most suited for linear processes only [Chen, 1996; Astrom & Hagglund, 2001, Ang, Chong & Li, 2005]. In case of shakers, PID variants like filters for oscillatory systems have also been experimented and reported in the literature [Uchiyama, Mukai & Fujita, 2009].

For the last three decades, the dramatic development of inexpensive and powerful computer technology has radically changed the boundaries of control systems. Computer controlled digital systems are especially useful for control of complex systems. It is now possible to employ, complicated and higher order digital controllers, to carry out the complex control tasks. With the advent of high speed digital computers, computational complexity is not a limitation anymore because the computing power has been significantly improved even for high speed industrial processes like shakers. This makes the FLC an important and efficient alternative method for use in complex un-modeled and nonlinear systems like shakers as these are adaptive in nature. As pointed out earlier, for control of these devices most of the work has been in the typical frequency domain control approach. This approach requires process identification at regular intervals (for transfer function equalisation) during the sine sweep tests, which is a time consuming process in contrast to FLC which is a model free approach.

The main aim of this research is to develop and implement an intelligent fuzzy logic acceleration amplitude control algorithms for acceleration control of electrodynamic shaker system. Fuzzy PI controller was experimented in this research for the acceleration magnitude control. Two experiments, on the shaker acceleration control mechanisms, were conducted using the FLC. In an initial experiment, an in-house developed shaker was used. The prototype single degree of freedom shaker was developed in-house for the research and laboratory purposes. This prototype shaker worked in a relatively low frequency band. The overshoot, settling time and the rise time parameters were used as the performance criterion. The rigid test load was used as the payload for
vibration testing in this experiment. The performance of the fuzzy controller was also compared with the conventional PI control mechanism. The conventional controller was designed based on the direct synthesis method. FLC is found to be outperforming the PI controller in this experiment.

In another experiment, an industrial grade single degree of freedom electrodynamic shaker was used. The fuzzy control was implemented on waveform-by-waveform basis through closed loop in typical automotive and aerospace tests frequency range (10Hz – 2 kHz). The main control variable is the shaker’s table acceleration amplitude. The error and the change of error in the acceleration waveform amplitude were minimized using a customized FLC to achieve the control objectives. The developed intelligent control mechanism makes it possible to perform tests, such as fatigue life, evaluation of resonant frequencies, replication of acquired acceleration’s field signals, dwell sine test, fall, general modal analysis etc. and all the other tests which are bound in frequency and amplitude. A practical approach has been presented and the developed mechanism can be scaled to other industrial shakers with little effort.