

# Fuzzy Control Of A Vibration Actuator

K. P.S RANA, R. SINGH and K. S. SAYANN

*Abstract-* A fuzzy logic based digital sinusoidal acceleration waveform amplitude controller for a PC based electrodynamic vibration actuator is presented. The fuzzy logic control (FLC) purpose is to reproduce pre-defined sinusoidal acceleration amplitude at the vibration table of a vibration actuator system. Sinusoid vibration profiles (sine and linear sine sweep) are considered for a closed-loop controlled vibration generation for rigid load. The difficulty in sine vibration generation is the un-modeled and complex non-linear dynamics of the vibration actuator system. To cater to the needs of a sine sweep vibration generation, the controller needs to be robust to un-modeled dynamics of the vibration actuator system as well as sufficiently fast to hold the specified acceleration amplitude. The performance of the developed control logic is tested in real time using LabVIEW based virtual instrumentation (VI) tools for vibration signal acquisition and measurement on the in-house designed and developed prototype shaker system for reference tracking and disturbance rejection. The performance of the proposed solution is also compared to a classical conventional Proportional and Integral (PI) control. FLC is found to be faster and more robust to un-modeled dynamics of the shaker system. Furthermore, the implemented approach is simple, straight forward and free from the un-modeled and complex dynamics of the vibration actuator system. The actuator design, FLC synthesis, implementation and comparative study with a PI controller in real time are presented in this paper.

*Index Terms*—Electrodynamic vibration actuator, Fuzzy logic controller, Vibration control, Acceleration control.

## 1. INTRODUCTION

Vibration is one of the most classical phenomena and it attracted minds of great scientists' right from the days of Sir Issac Newton. A mechanical vibration in particular has many applications such as stimulus response analysis, reliability testing, and sine sweep testing and resonance study. Vibration testing refers to subjecting a device to some pre-defined profile of mechanical vibrations in terms of amplitude and frequency. Various industries like defense, space, railways, airways and embedded hardware manufacturing, during the critical phase of testing of their products, require vibration tests of precisely defined profiles. In general there is a great demand on increasing the reliability of devices making use of critical components. This is accomplished by intensive vibration tests as this is the main phenomenon

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F. Author is with Dept. Instrumentation and Control Engineering., Netaji Subhas Institute of Technology, Delhi University, Sector 3, Dwarka, New Delhi 110078, India (e-mail: kpsrana1@gmail.com); S. Author is with Indian Society for Technical Education, Shaheed Jeet Singh Marg, New Delhi – 11 00 16, India; T. Author is with Guru Teg Bahadur Institute of Technology, Guru Gobind Singh Indraprastha University, G-8 Area, Rajouri Garden, New Delhi – 11 00 27, India

responsible for the durability and the serviceability study of various devices. In fact vibration tests have become one of the essential tests for all the test and measurement systems including the tiny gadgets like personal digital assistants and home appliances. Vibration testing also plays a major role in identifying faults in machineries and in prevention of failures leading to the mechanism of fault diagnostics [3, 14].

The main aim of this work is to design and develop a PC based single degree of freedom prototype vibration actuator system, and to develop and implement an intelligent fuzzy logic acceleration waveform amplitude control algorithm through closed-loop in relatively moderate frequency range from 50Hz-1 kHz.

### 1.1 Bibliographical Review

This section describes the related work on analysis, modeling and control mechanisms of electrodynamic vibration actuators. The design technique of industrial vibration actuator controllers for sine vibration generation is essentially a frequency domain approach, usually referred to as transfer function equalisation; before starting the test, the controller outputs a broadband random excitation signal to the actuator. Based on the measured response, the inverse transfer function of the vibration generation process is computed. This information is then used to generate the control signal such that the process dynamics are compensated to match the desired input magnitude profile. During the test execution, the controller constantly monitors response acceleration and updates the inverse transfer function [21]. As reported in [29], this technique relies on the use of selective tracking filters to attenuate any frequency other than the controlled one, which improves the measurement accuracy and keeps the focus on magnitude control instead of root mean square acceleration. This method of transfer function equalisation requires relatively longer processing time to manipulate blocks of data. The resulting delays in updating the drive signal in response to changes in input acceleration makes it difficult to achieve stability and good reference tracking particularly during the sweep test.

In [8], analysis and control of a moving coil electrodynamic vibration actuator is presented. A linear model is developed and controller is designed by pole placement technique. Pole placement control strategy has the effect of improving the shaker performance by reducing its sensitivity to harmonic content of the excitation waveform. The model is validated on a

physical system to some extent. The proposed model is unable to compensate for the un-modeled nonlinearities of an actuator which gives rise to irregularities in the mid-band frequency response. Furthermore, the experiment is performed on a bare table and the performance of sine sweep test and loaded table has not been investigated and reported.

In [19], a digital acceleration controller for sinusoidal vibration tests using a switching-mode AC power source (ACPS) for an electrodynamic vibration actuator is presented. The proposed scheme makes use of two interactive control loops. One of the loops is used for the acceleration regulation and the other one is used for ACPS voltage output control. A robust model reference adaptive control algorithm is used to reduce the effects caused by the variations of the shaker 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 low frequency band of 20Hz-200Hz. A digital acceleration controller in time domain for sine vibration testing on an electrodynamic vibration actuator by the same authors is presented in [20]. Sample-by-sample control for faster drive signal correction is implemented. The controller structure is developed based on the usual vibration testing power amplifier technology in the automotive range. A detailed procedure for shaker modeling and control logic development is presented and supported by the experimental results. An acceleration tracking accuracy of 10% is claimed for sine sweep test. The control mechanism used is based on the series of compensators and filters. The suspension and coil mode compensators are derived from the measured parameters of the shaker. Three compensators are used to obtain the flat frequency response and the acceleration tracking. The used acceleration reference tracking compensator needs to be tuned continuously for excitation frequencies. Furthermore, the performance of the system depends on the model approximated using the basic measurements made on the shaker system. The shaker being complex has un-modeled and complex dynamics.

In [22], a fast Fourier transform (FFT) based variable sampling rate method for sine magnitude control is presented. According to simulation results, this approach has improved the amplitude identification accuracy without using tracking filters, which significantly increases the controllers' response and precision during the frequency sweep. However, experimental verification and validation of the proposed method has not been presented.

In [26], a state variable system graph-theoretic approach is adopted and an electrodynamic shaker system is shown to be completely controllable and completely observable. However, no controller is

proposed and no closed-loop performance on the actual hardware system is investigated and reported.

In [28], an analog PI controller is used to track the acceleration amplitude of an inverter-fed electrodynamic shaker. The plant is approximated to a first order transfer function and the controller is designed for zero steady-state-error and a known time constant in step response. Robustness to parameter variations are demonstrated experimentally. This scheme specifies drive signal instead of the shaker excitation voltage. Being an internal state of an amplifier, it strongly prevents its application to the usual vibration actuator and power amplifier technology in vibration generation. Results for sine sweep tests have not been investigated and reported.

In [30], electrodynamic vibration actuator robust control is obtained by means of two controllers. Two control variables used are acceleration and displacement of the shaker's table respectively. This mechanism offers shaker control in broad frequency band. Acceleration control is employed in higher frequency range and displacement control in lower frequency range. Both mechanisms are coupled in a cascade mode. Finally, the control mechanism is validated on an electrodynamic vibration actuator and some comparisons are drawn. However, no test for sine sweep vibration generation has been conducted and reported.

A fuzzy logic controller for random vibration testing is proposed and studied in simulation in [13]. Linguistically approached self-organizing fuzzy control law is adopted. The results of simulation show that the fuzzy controller can effectively overcome the distortion and nonlinearity of the vibration testing system.

Literature survey on the electrodynamic vibration actuator control conducted above clearly indicates that controlled vibration generation for vibration testing has been a demanding area of research for the applications cited above in vibration testing in an era of enhanced quality requirements. An electrodynamic vibration actuator 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 power excitation. Additionally, test load dynamics changes the mechanical parameters of the shaker, especially the mass. Actuator spring-mass suspension resonances and modeling errors equally contribute to make almost unusual open loop operation of vibration systems [6-8]. Furthermore, the shaker input exciting signal has variations in the frequency and amplitude along with the disturbances offered by the test specimen dynamics. These factors make the shaker system one of the most promising process candidates for the non-linear control applications [5]. For a constant amplitude sinusoidal input excitation signal, the

vibration amplitude changes markedly with frequency. More recently PC based systems are being used to implement the digital controllers and compensators to obtain the control objectives in real time. Limited types of vibration controllers have really been studied and actually implemented for vibration control on the shaker systems in contrast to the process control industry. Another aspect is the comparative study and performance evaluation of various controllers. The shaker system development and so its controllers have been mainly 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 experimented on the complex systems like electrodynamic vibration actuators. In contrast to the process control technologies, where large varieties of controllers have been studied and implemented, the work available in shaker control domain is very limited. Bridging such technical gap is one of the main advances of the proposed research.

It may be noted that PID control, which shares around 90% of the process industrial controllers' space, are most suited for many industrial processes. Furthermore, it is much matured technology and has set guidelines for tuning. PID controller has witnessed a long journey in its development over the years [15, 25]. With the advent of high speed 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 FLC an important alternative method for use in complex un-modeled and non-linear systems [10, 27].

The main aim of this work is to design and develop a single degree of freedom prototype PC based vibration actuator system and to develop and implement an intelligent fuzzy logic acceleration magnitude control algorithm through closed loop in a relatively moderate frequency range. The main control variable is the shaker's table acceleration waveform amplitude. The error and the change of error in the acceleration magnitude are minimized using 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 and general modal analysis, and all the other tests which are bound in frequency and amplitude. The developed mechanism is simple and can be scaled to industrial shaker systems with little effort. The performance of the developed control mechanism is compared to the classical PI control.

The paper is organized as follows. Section 2 presents the design data of an in-house developed PC based prototype vibration actuator system. The main aim of the system development has been the prototype

laboratory model for teaching and research for low weight payload (~200grams) in a moderate frequency range (50Hz–1 kHz). Section 3 presents a design approach to the acceleration waveform amplitude control using a conventional PI control method and FLC. Implementation procedure is described in block diagram form. FLC implementation procedure including synthesis, I/O variables, discretization, normalization, resulting control surface and the tuning mechanism employed are presented. Section 4 presents the experimental setup and results. Detailed hardware and software components used and their interfacing are presented in a block diagram form. Open loop system characterization, plant identification and comparative performance study are given. Acceleration magnitude tracking results for step change of reference acceleration amplitude for bounding frequencies, i.e., 50Hz and 1 kHz are presented. Disturbance rejection has also been studied and results have been presented. Finally, a sine sweep test performance of the two controllers is investigated and results are presented. Section 5 presents the conclusion and discussion.

## **2. MODERN ELECTRODYNAMIC VIBRATION ACTUATOR SYSTEM COMPONENTS AND DESIGN**

A vibration actuator system is a device that applies the mechanical vibrations to a test specimen as per the predefined acceleration profile, i.e., acceleration magnitude, frequency and time. The working principle of the shaker under consideration may be different depending on the concept utilized, i.e., electrodynamic, hydraulic or pneumatic. In this experiment, a prototype PC based electrodynamic vibration actuator is designed and developed in-house for teaching and research purpose. It is composed of three main components: a vibration exciter, a power amplifier and a digital control system. Fig. 1 shows the various components required for a closed-loop PC based vibration generation and control. The vibration exciter transforms the electrical energy fed to it into physical movements, i.e. mechanical vibrations. The interface to the PC is twofold. First, it is used for measurement of generated vibrations, and, second it generates the base controlled signal for the power amplifier. It may be noted that the general purpose data acquisition (DAQ) card used in the experiment under consideration are designed for  $\pm 10V$  and 4-20mA output ratings. So, these cards cannot drive the shaker requiring high armature current directly. The DAQ card, being fully programmable, allows users to generate complex waveforms and apply the intelligent digital controller requiring lots of programming capability. Hence, in the PC controlled vibration actuators, the DAQ device generates the base signal as per the desired profile in amplitude, frequency and time.

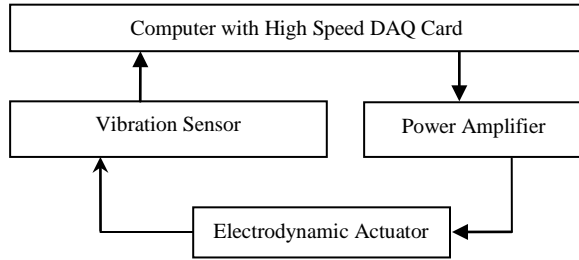


Fig. 1. Computer controlled electrodynamic vibration actuator system.

This signal is further amplified by the power amplifier to cater to the needs of the shakers for higher current requirements. The digital controller monitors the vibration test in real time. It guides the DAQ card signal for the required changes so as to meet the target vibration profile. The power amplifier, used in such applications, requires some features that are not necessary on other common applications. The amplifier distortion is one of the main features of concern for shakers in addition to the flat frequency response on a wide operating frequency band.

The moving coil principle is almost universal in electrodynamic vibration actuators for vibration testing. As in the loudspeakers whose construction matches to that of electromagnetic shakers, it is found that the linearity (i.e. thrust per current invariance with frequency and with moving element instantaneous position) achievable over a wide frequency range by moving-coil shakers is virtually unrivalled [24]. The electrodynamic vibration actuator works on the basis of the electromagnetic force generated between two interacting magnetic fields. One of them, the moving coil called armature, has its own magnetic field proportional to the applied voltage. The control mechanism in the electrodynamic vibration actuator is achieved by controlling the voltage applied to moving coil. The other field is static and normally generated by a permanent magnet or DC excited coil. In the prototype shaker developed, the DC excited fixed coil is used as field coil. Thus, there is a fixed armature for field coil and another acting one supports the test specimen where the acceleration is measured for the active control. A prototype PC based laboratory education and research model of electrodynamic vibration actuator is developed. Table 1 gives the design data of the developed shaker. Figs. 2 and 3 show the internal view schematic and the snap shot of the developed prototype electrodynamic vibration actuator [6, 7]. The developed shaker system is designed for low weight payload (~200grams) and a maximum of 5g acceleration.

### 3. ACCELERATION WAVEFORM AMPLITUDE CONTROLLER

#### 3.1 Fuzzy Logic Controller Design

Table 1: Design details of developed vibration actuator

Physical Details	Electrical Details
Electromagnet- No. of Turns: 20800 Length: 45mm Inner Dia.: 68mm	Electromagnet- Current: 100mA Voltage: 100VDC
Moving Coil- No. of Turns: 160 Length: 100mm Inner Dia.: 47mm Weight: 180grams	Moving Coil- Current: 3A(rms) Thrust: 35N Resistance: 6Ω Acceleration: 5g Frequency: 50-1kHz

Emerging intelligent techniques have been developed and extensively used to improve or to replace conventional control techniques because these techniques do not require a precise model. One of the intelligent techniques, fuzzy logic, developed by Lotfi A. Zadeh, is applied for controller design in many applications. FLCs have shown some success, but there is a significant need to evaluate their real time performance on specific experiments. Such evaluations help to determine the performance of the new intelligent control method and provide engineers with general guidelines on how to apply them to more complex real-world applications [12, 16, 17]. FLC has emerged as one of the most active and useful research areas. That is why; the FLCs have been successfully applied for control of various physical processes. Basically there are two approaches to a FLC design: an expert approach and a control engineering approach. In the first, the FLC structure and parameters choice are assumed to be the responsibility of the experts. Consequently, design and performance of a FLC depends mainly on the experts'

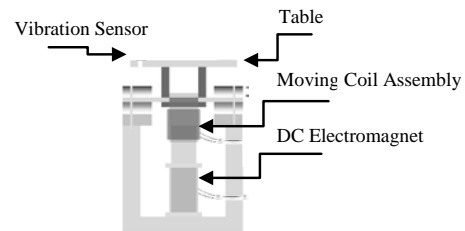


Fig. 2. Schematic of the electrodynamic vibration actuator system.



Fig. 3. Developed electrodynamic vibration actuator system.

knowledge and experience, or intuition and professional feeling of the designer. This dependence, which is considered far from being systematic and reliable, is the flaw of this approach. However, this approach could assist in constructing a fuzzy model or an initial version of a FLC. The second approach supposes an application of the knowledge of control engineering and a design of a fuzzy controller in some aspects similar to the conventional design with the parameter's choice, depending on the information of their influence on the controller performance [1-2]. Despite a lot of research and large number of different solutions proposed, most industrial control systems are still based on conventional PID regulators. Different sources estimate the share taken by PID controllers to be over 90%. The main reason is due to their low cost, inexpensive maintenance, simplicity of operation, ease of design and hardware as well as software implementations, and effectiveness for most systems [5, 18, 25]. In electrodynamic vibration actuators, analog PI control [28] has been implemented as acceleration amplitude controller in some cases as it has the advantage of easy implementation. However, conventional controllers do not provide a general solution as the shakers normally have inherent non-linearity and hence offer limitations to conventional control. The electrodynamic vibration actuator system is in general complex and time-variant, and often with poorly defined dynamics. When the process becomes too complex to be described by analytical models, it is unlikely to be efficiently controlled by conventional approaches. To overcome these difficulties, various types of modified conventional PID controllers such as auto-tuning and adaptive PID controllers are developed [6, 18]. Also, a class of non-conventional type of PID controllers using FLC has been designed and simulated for the purpose [6, 9, 11].

The present research work is focused on the design and implementation of a fuzzy PI controller on an electrodynamic vibration actuator acceleration magnitude control. The error and the change in the error of the acceleration waveform amplitude are minimized to achieve the control objective. A fuzzy PI controller is chosen and designed on the basis of the classical discrete PI controller structure, from which the fuzzy

control law is derived [23]. Fig. 4 shows the acceleration magnitude controller implementation scheme.

### 3.1.1 Fuzzy PI Controller Design

A classical PI controller is described by

$$u_{PI}(t) = K_C(e(t) + \frac{1}{\tau_I} \int e(t)dt) \quad \dots(1)$$

where  $K_C$  is the proportional constant of a PI controller,  $\tau_I$  is the integral time constant,  $e(t)$  is error in the acceleration amplitude,  $e(t) = r(t) - y(t)$ ,  $r(t)$  is the desired acceleration amplitude,  $y(t)$  is the output acceleration amplitude obtained at the shaker table and  $u_{PI}(t)$  is the output of the controller as shown in Fig.4. On differentiating (1) and putting into a discrete form,

$$\frac{du_{PI}(t)}{dt} = K_C \left( \frac{de(t)}{dt} + \frac{1}{\tau_I} e(t) \right),$$

or  $\frac{[u_{PI}(k) - u_{PI}(k-1)]}{T_S} = K_C \left( \frac{[e(k) - e(k-1)]}{T_S} + \frac{1}{\tau_I} e(k) \right)$ , where  $T_S$  is the sampling period. On further simplification,

$$du_{PI}(k) = K_C [de(k) + \frac{T_S}{\tau_I} e(k)],$$

where,  $de(k) = e(k) - e(k-1)$ , is the change of error and  $du_{PI}(k) = u_{PI}(k) - u_{PI}(k-1)$ , represents the change in the controller output. On further implication,

$$du_{PI}(k) = K_C de(k) + K'_C e(k) \quad \dots(2)$$

where,  $K_C$  and  $K'_C = \frac{T_S}{\tau_I}$  are constants for a given  $T_S$ ,

$$\text{thus, } u_{PI}(k) = u_{PI}(k-1) + K_{UPI} du_{PI}(k) \quad \dots(3)$$

where,  $K_{UPI}$  (Gain PI) is introduced as the fuzzy PI controller gain.

To implement a fuzzy PI controller (2), two inputs namely the instantaneous acceleration waveform amplitude error  $e(k)$  and the change of the error  $de(k)$  are required and the output of the FLC is the incremental amplitude change in the controller output waveform amplitude to be fed to the power amplifier. Increasing the number of inputs to FLC would require more processing time for the larger rule base size and hence would force a constraint on the implementable real time signal update rate. In the vibration control, fast computation offers higher drive signal update and sine sweep rate as it would take less time to attain the desired acceleration amplitude at a given frequency i.e. before a new frequency line is swept the controller must ensure the settling of the previous frequency line.

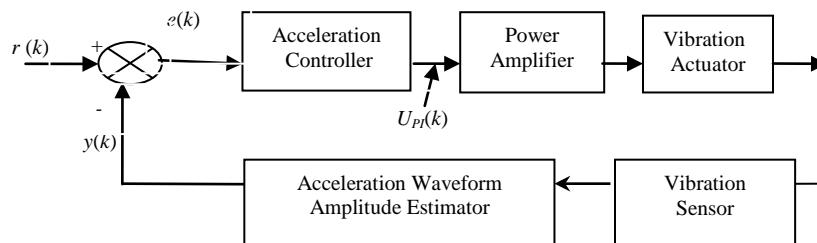


Fig. 4. Acceleration waveform amplitude control in close loop

In order to make the computations faster Fuzzy PI controller is chosen rather than other combinations such as Fuzzy PI + Fuzzy PD or Fuzzy PID itself. A physical meaning of the parameters for the fuzzy PI controller remains the same as that of the PI controller. Fig. 5 shows the block diagram for implementation of a proposed fuzzy PI controller for the acceleration waveform amplitude controller. The controller takes two fuzzy variable  $e(k)$  and  $de(k)$  as input and gives the incremental change of the control action.

3.1.2 Pre-requisite of the FLC implementation

Implementation of the FLC requires some preprocessing. This section details the various tasks and gives the details about the task accomplishment in the experiment under consideration. Fig. 6 shows the various modules required for FLC implementation.

Fuzzification - Input and output variables of the FLC are usually quantized into sets of classes defined by linguistic labels. For this experimentation, the inputs and outputs are quantized into seven fuzzy sets, namely: PB – Positive Big, PM – Positive Medium, PS – Positive Small, ZE – Zero, NS – Negative Small, NM – Negative Medium and NB – Negative Big. This quantization of the fuzzy variables is carried out in the normalized range of [-1, 1] for inputs as well as for output. The membership functions for  $e(k)$ ,  $de(k)$  and  $du(k)$  are all of triangular type with 50% overlap as shown in Fig.7. Triangular membership function is

chosen as it is the most economical one. The computational requirements are least in triangular membership functions and these are most suited for real time control applications.

Rule base - The rule base for FLC can be imagined to be a two dimensional matrix as summarized in Table 2. The rows represent the various linguistic values that  $e(k)$  can take and columns indicate the various values of  $de(k)$ . The entries in this matrix would be the control action that has to be taken in the linguistic terms. The control action is calculated based upon the experimentally observed process reaction [1, 2]. Fig. 8 shows the fuzzy surface formed by the various values of the two fuzzy inputs namely,  $e(k)$  and  $de(k)$  and a fuzzy output  $du(k)$ .

Fuzzy Inference Engine - The basic function of the fuzzy inference engine is to compute the overall value of the control output variable based on the individual contribution of each rule in the rule base. For the present research work, Mamdani inference mechanism has been used. The differences in using the various implication techniques are described in [4]. It is observed that Mamdani’s technique is most suitable for hardware implementation due to simple *min-max* structure. The first phase of Mamdani’s implication involves *min*-operation since the antecedent pairs in the rule structure are connected by a logical ‘AND’. All the rules are then aggregated using a *max*-operation [16, 17].

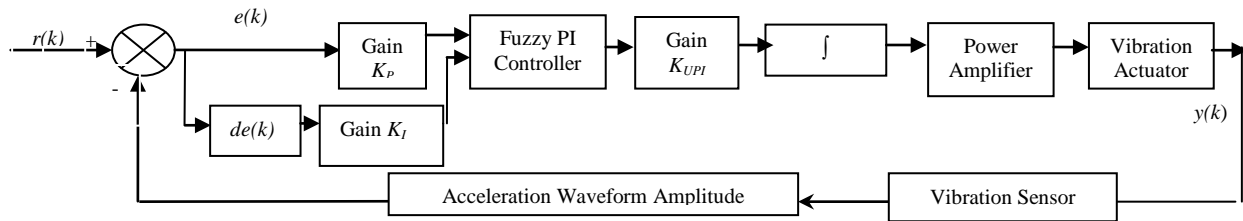


Fig. 5. FLC based acceleration waveform amplitude control in close loop.

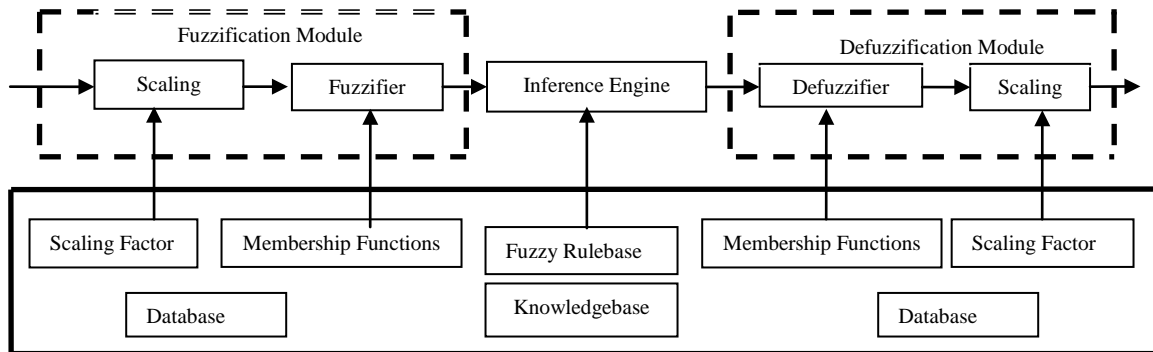


Fig. 6. FLC implementation modules.

Defuzzification – This module converts the set of modified control output values into a single crisp value. There are many procedures outlined in the literature for defuzzification which is, centre of gravity/area, centre of mass, centre of largest area, first of maxima, middle of maxima, and height. Of these the centre of gravity (COG) is the most efficient in that it gives a defuzzified output which conveys the real meaning of the action that had to be taken at that instant. So, in the present work, the center of gravity defuzzification method is used to defuzzify the fuzzy sets into a crisp control signal [18].

### 3.1.3 Tuning

The tuning of a fuzzy controller is often compared to the tuning of a PID, stressing the large number of the fuzzy controller parameters, compared to the three gains of a PID. In the experiment conducted, tuning is done manually by optimizing the run time step response of the shaker acceleration amplitude. For performance comparison with PI control both the controllers are tuned at 1 kHz shaker excitation having almost similar performances.

### 3.2 PID Controller

Comparative study of the proposed FLC is carried out with the conventional PI controller. Conventional PI controller has been used in some cases as acceleration amplitude controller [28]. The structure of a PI controller algorithm implemented is given in (1). The shaker acceleration waveform amplitude response is approximately expressed by a first order transfer function

$$H_a(s) = \frac{\text{Response acceleration amplitude (s)}}{\text{Excitation voltage amplitude (s)}},$$

$$= \frac{K_a}{\mu_a s + 1} \dots\dots (4)$$

where,  $K_a$  is the process gain and  $\mu_a$  is the process time constant. The acceleration amplitude controller is designed using direct synthesis technique and chosen to be of the following PI type.

$$G_a(s) = \frac{K_{AP} s + K_{AI}}{s} \dots\dots (5)$$

Before performing the controller design, the plant model  $H_a(s)$  is estimated from the measured step response of the plant. This is done by exciting the shaker at 1 kHz and varying the input excitation voltage in predefined steps. In the controller design, the closed loop first order transfer function with zero steady-state error and desired time constant ( $\mu_{ad}$ ) in step response is specified [28].

$$H_{ad}(s) = \frac{1}{\mu_{ad} s + 1} \dots\dots (6)$$

The controller parameters of  $G_a(s)$  are therefore found to be,

$$K_{AI} = \frac{1}{k_a \mu_{ad}}, K_{AP} = \frac{\mu_a}{K_A \mu_{ad}} \dots\dots(7)$$

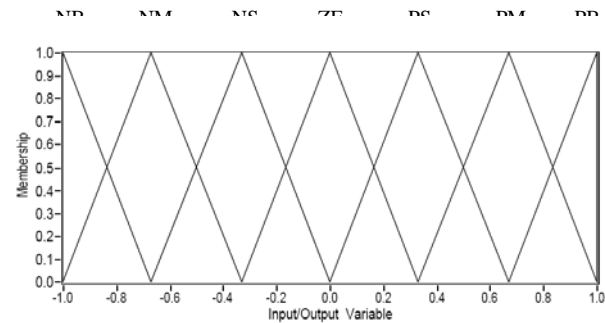


Fig. 7. Triangular membership functions and fuzzy variables.

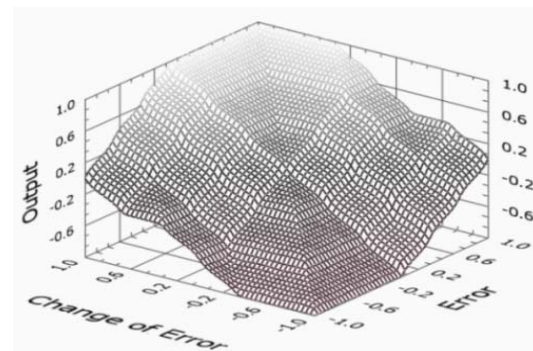


Fig. 8. Fuzzy control surface for two inputs and one output of the fuzzy controller.

Table 2: Rule base for fuzzy PI controller

		Change of error ( $de$ )							
		NB	NM	NS	ZE	PS	PM	PB	
error ( $e$ )	NB	NB	NB	NB	NM	NS	NS	ZE	
	NM	NB	NM	NM	NM	NS	ZE	PS	
	NS	NB	NM	NS	NS	ZE	PS	PM	
	ZE	NB	NM	NS	ZE	PS	PM	PB	
	PS	NM	NS	ZE	PS	PS	PM	PB	
	PM	NS	ZE	PS	PM	PM	PM	PB	
	PB	ZE	PS	PS	PM	PB	PB	PB	

### 3.3 Performance Criteria

For controlling the acceleration magnitude of the electrodynamic actuator system, the main performance evaluation criteria taken are peak overshoot and settling time. This is because in the vibration testing, the profile is defined for a given acceleration magnitude. In sine sweep test the actuator is required to maintain the desired acceleration amplitude throughout the sweep cycle. Minimizing the settling time would give faster acquisition of the desired profile. Furthermore, the minimization of overshoot lets the device being tested for precise acceleration limits profile. Thus, the main factors which have been considered for evaluating the performance are the overshoot and settling time. Overshoot is controlled within the 10% accuracy for the bare table and with some small rigid load using FLC in the entire frequency range without using any other additional compensators. The main settings which have to be done in the system are for the desired acceleration magnitude at given frequency for reference tracking. For sine sweep acceleration control, the frequency of excitation is varied at a given rate and the performance of the controller is observed during the sweep.

## 4. EXPERIMENTAL SETUP AND RESULTS

This section explains the details of the experimental setup used to carry out the experiment. Results of some open-loop test conducted to characterize the developed shaker and the used power amplifier on various parameters are also listed. The open-loop frequency response of the shaker and the used power amplifier are measured and presented. Effect of voltage variation on the acceleration magnitude generated by the shaker is also studied and presented. All these tests are required to know the capability and limits of the developed system. Fig. 9 shows the various hardware and software components with their technical details including the make and model used to measure and control the developed vibration actuator system. The developed shaker system makes use of power amplifier (Model LDS PA-100E from M/S Ling Dynamic System). LabVIEW 8.6 (M/S National Instruments) software package along with add-on Sound and Vibration toolkit and Fuzzy logic toolkit modules are used to develop a VI for carrying out the measurement and control objectives. Fig. 10 shows the snap shot of the experimental setup developed. Fig. 11 shows the flow chart for the VI developed for measurement and control of the shaker. The front panel of the developed VI is shown in Fig. 12. It has the interfaces for setting the frequency and reference acceleration magnitude. A user interface for channel selection, setting the maximum limit of the DAQ output and sampling rate are provided on the VI developed. Additionally various graphical interfaces as can be seen in the tab of the VI are for viewing the current excitation signal waveform, acquired acceleration waveform, acceleration magnitude, frequency spectrum (FFT) of the acquired acceleration

vibration signal and error between the reference and the acquired acceleration magnitude. Data acquisition card (NI-DAQ-6281) is used to acquire the vibration signal and also to generate the base control signal for the power amplifier. Shear type accelerometer (Model 8704, ICP based, 4mA excitation, acceleration range  $\pm 50g$ , sensitivity 100mV/g, 10 kHz frequency range by M/S Kistler) is used to sense the acceleration. For signal conditioning of the vibration signal, NI-SCXI chassis-1000+1530 accelerometer input module is used. Both input and output are sampled at 40kS/s. The excitation of the shaker is done on a complete waveform basis. In all input and output operations, data of 40ms duration

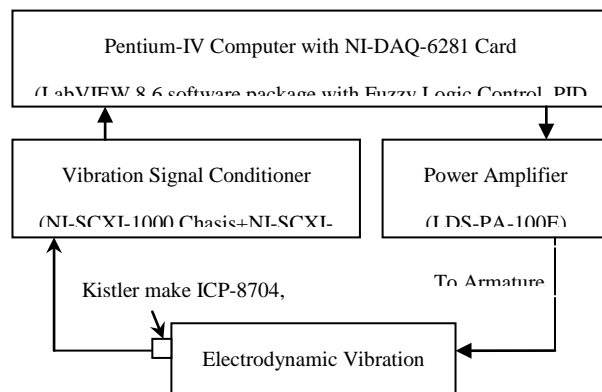


Fig. 9. Experimental setup.

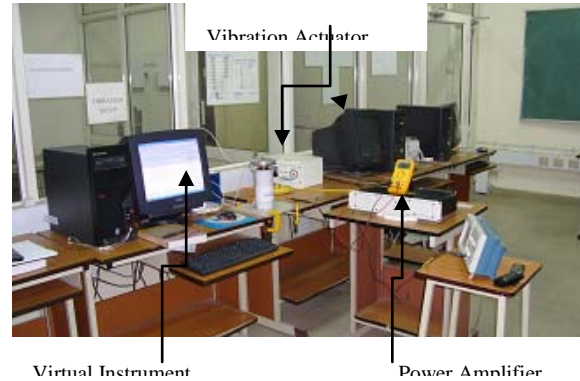


Fig. 10. Snap shot of the experimental setup.

are transferred in the block of 1600 samples. Hence the corrective action of the controller gets updated every 40ms. Also 40ms is the loop time.

The timing aspect of FLC has also been studied. As compared to PI, the FLC is more expansive and resource demanding. In this experiment, the FLC of seven membership functions, with two input variables forming 49(7x7) rules, takes an average time of 100 $\mu$ s per iteration. It may be noted that this time is much smaller than the 40ms time for one cycle execution.

The frequency response of the power amplifier, the effect of the voltage variations on the acceleration magnitude and the frequency response of the shaker in open-loop configuration are also studied. The measured frequency response of the power amplifier is shown in Fig. 13. It shows some reduction in gain at frequency below 200Hz. Furthermore, the shaker frequency response at a given excitation voltage (2V) and the effect of voltage variation at a given frequency (1 kHz) excitation are conducted. The frequency response of the shaker is shown in Fig. 14. As expected the two resonances are observed at around 20Hz and 1450Hz. The lower resonance at around 20Hz is attributed to the

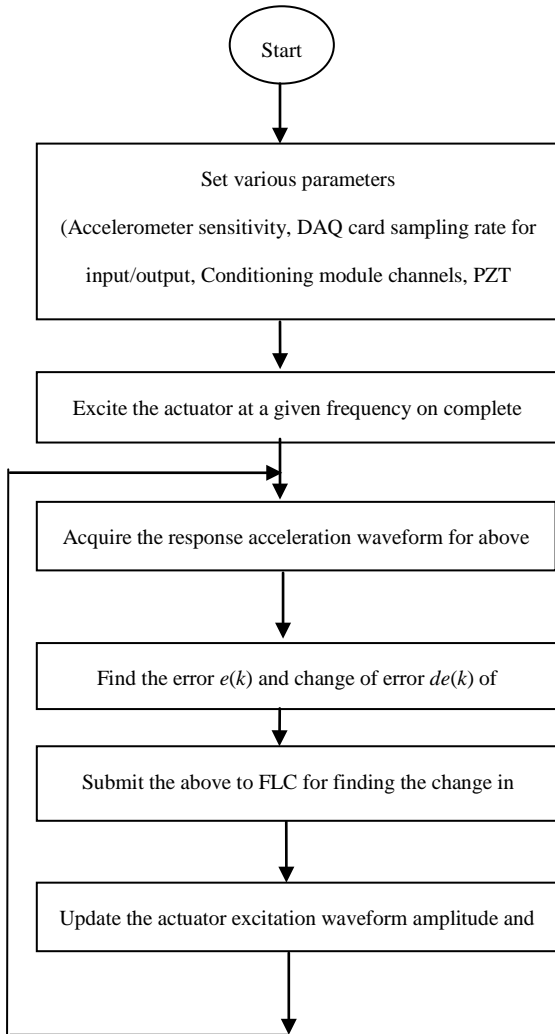


Fig. 11. Flow chart for vibration actuator control.

spring mass suspension system. On the other hand the high frequency resonance is attributed to the moving coil, adhesive bonding and table. The operating resonance free frequency band for the developed actuator is thus around 50Hz-1 kHz. The effect of the excitation voltage amplitude variation at 1 kHz is shown in Fig. 15. As seen in Fig. 15 the response to voltage variation is nearly linear. These studies have been very useful tools for estimating the capabilities of the experiment under consideration.

For process identification of the shaker and power amplifier combination let the control loop be opened and the input excitation voltage amplitude at 1 kHz be varied in steps of 2V several times in either direction. The excitation signal and the received acceleration amplitude response is recorded and shown in Fig. 16. The dynamic model of the plant  $H_a(s)$ , is estimated using the parametric model estimation technique. The controller parameters are derived as mentioned earlier

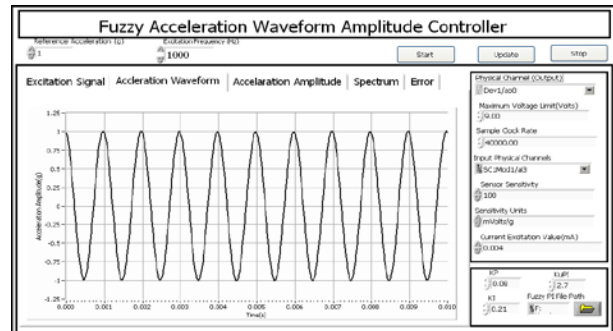


Fig. 12. Front panel of the VI developed for acceleration magnitude controller.

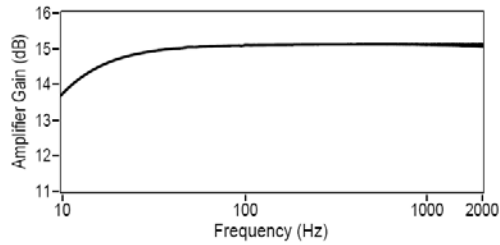


Fig. 13. Frequency response of power amplifier.

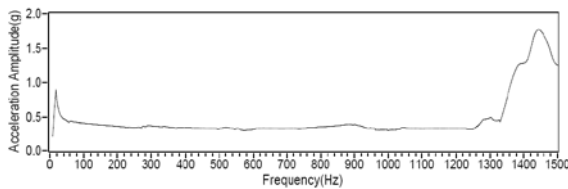


Fig. 14. Measured open-loop frequency response of actuator (@2V).

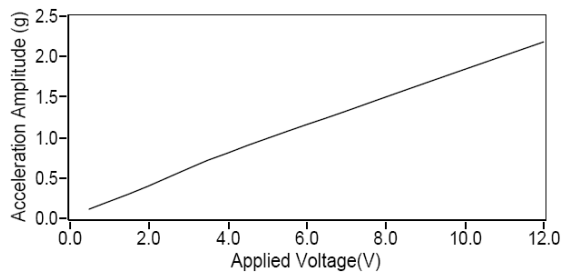


Fig. 15. Effect of voltage variation on shaker response (@ 1 kHz)

for time constant ( $\mu_{ad}$ ) of 0.4s. Fig. 17 shows the performance of the estimated model, as can be seen the measured and the predicted performance are same, thus validating the model.

$$H_a(s) = \frac{0.166}{0.4s + 1} \quad \dots\dots (8)$$

$$G_a(s) = \frac{6s + 15.00}{s} \quad \dots\dots (9)$$

The developed fuzzy controller is tuned manually for the almost similar performance as PI at 1 kHz and the fuzzy gains are obtained as  $K_c = 0.08$ ,  $K'_c = 0.21$  and  $K_{UPI} = 2.7$ . Fig. 18 shows the reference tracking performance of fuzzy PI and conventional PI control. At 1 kHz excitation the reference acceleration magnitude is

set for 1g and 2g acceleration amplitude alternatively several times and the response is recorded. The plot shows the variation of the acceleration magnitude (step response) vs. iteration count. As mentioned earlier the 100ms time is consumed per iteration. As seen clearly similar performance for both the controllers are obtained. Similar exercise is conducted at other end of frequency at 50Hz. Fig. 19 shows the variation of the acceleration magnitude vs. iteration count. As seen in Fig. 19 PI control shows larger overshoot in comparison to fuzzy PI. This is attributed to the un-modeled dynamics of the shaker system. FLC being adaptive performs better to PI controller. Table 3 summarizes the comparison of the two control logics at these two frequencies. Estimation of overshoot, rise time and settling time is done for both the controllers. Rise time is defined as the time taken for attaining 90% of the final acceleration magnitude. Similarly the settling time is defined as the time taken to enter and remain in the 2% error band. It is noted that the FLC settles faster by 15%. Furthermore, PI produces a large overshoot of 16% as compared to 5.2% of fuzzy PI at 50Hz excitation, i.e., 67% more than fuzzy PI. Fig. 20 shows the FFT results for FLC and as seen clearly the frequency spectrum has a single peak of 2g at 1 kHz as expected.

Another similar exercise of reference tracking is done with small rigid load of 100grams. Figs. 21 and 22 show the acceleration tracking performance for both controllers under load at 1 kHz and 50 Hz. The overshoot is reduced at 50Hz but FLC here too performs better. Table 4 compares the results of two performances. It is noted that FLC again performs better than the PI. Disturbance rejection of the developed FLC is also investigated. For a reference acceleration of 1.5g a known disturbance of 0.5g is introduced and the tracking performance is studied. Fig. 23 shows the time

histories of the tracking performance under load of 100grams at 50Hz excitation. Here fuzzy PI responds faster with less overshoot. PI rejects the disturbance in 16 iterations against 9 iterations for fuzzy PI.

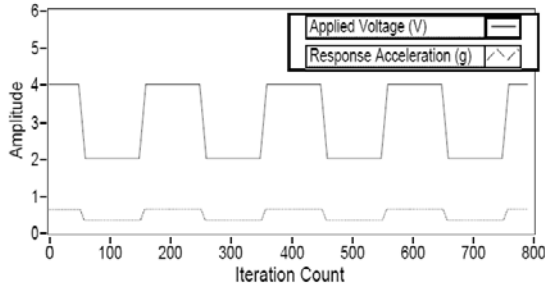


Fig. 16. Step excitation voltage and the response of the shaker.

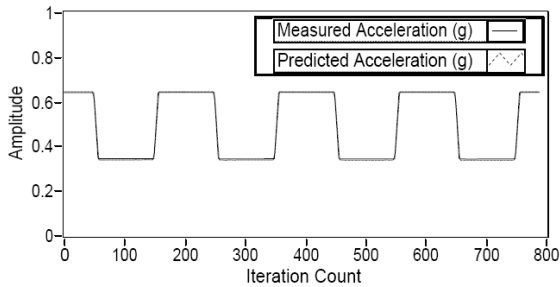


Fig. 17. Performance of the estimated model.

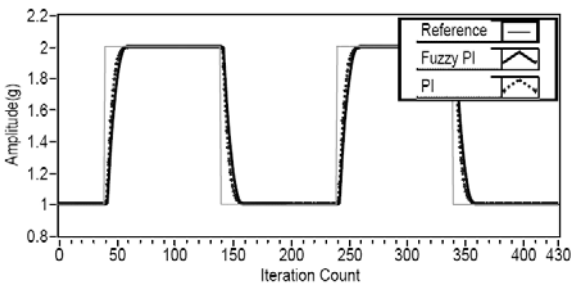


Fig. 18. Fuzzy PI and PI controller step response results for bare table at 1 kHz.

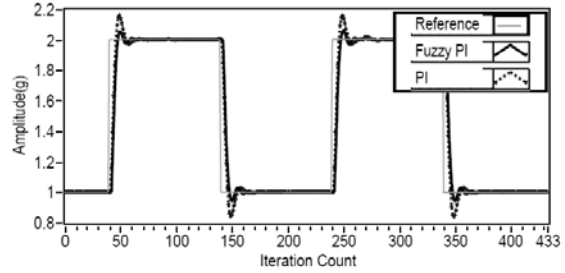


Fig. 19. Fuzzy PI and PI controller step response results for bare table at 50Hz.

Table 3: Acceleration amplitude tracking performance comparison for bare table.

Excitation Frequency	Type of Controller	Rise Time (Iteration)	Overshoot (%)	Settling Time (Iteration)	Remark
1kHz	Fuzzy PI	12	0.0%	16	FLC settles 15% faster
	PI	13	0.0%	19	
50Hz	Fuzzy PI	7	5.2%	17	FLC settles 15% faster and overshoots 67% less
	PI	6	16.0%	20	

To investigate the acceleration tracking performance in the entire frequency range of 50Hz-1 kHz, a linear sine sweep test under rigid load of 100grams is conducted at the sweep rate of 1octave/minute. Fig. 24 shows the result. As seen clearly the fuzzy controller maintains the error within a band of 10% in the full sweep cycle.

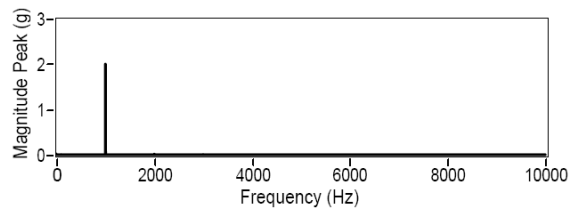


Fig. 20. Spectrum analysis (FFT) of the FLC controlled shaker output at 1 kHz.

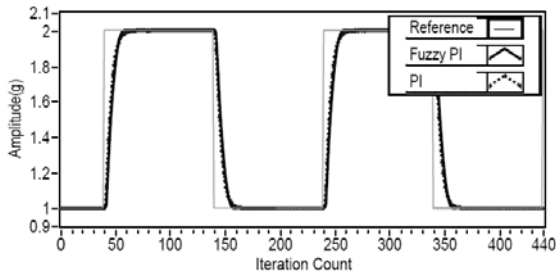


Fig. 21. Fuzzy PI and PI controller step response results for loaded table at 1kHz.

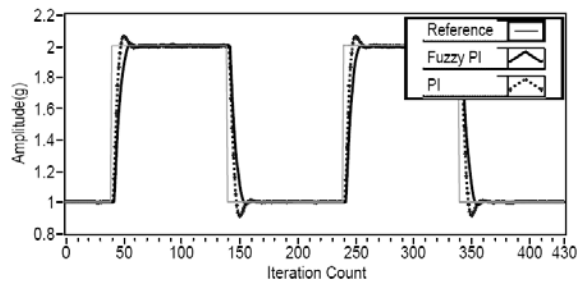


Fig. 22. Fuzzy PI and PI controller step response results for bare table at 50Hz.

Table 4: Acceleration amplitude tracking performance comparison for loaded table

Excitation Frequency	Type of Controller	Rise Time (Iteration)	Overshoot (%)	Settling Time (Iteration)	Remark
1kHz	Fuzzy PI	12	0.0%	16	Similar performance
	PI	13	0.0%	16	
50Hz	Fuzzy PI	11	1.4%	14	FLC settles 12% faster and overshoots 76% less
	PI	8	6.0%	16	

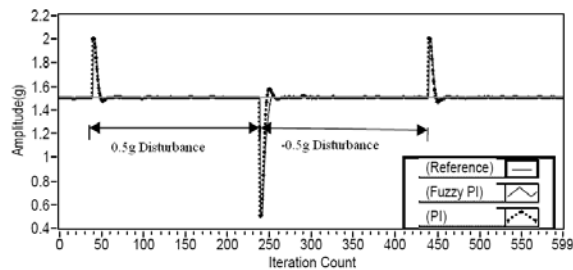


Fig. 23. PID and FLC performances for disturbance rejection at 1.5g reference acceleration magnitude.

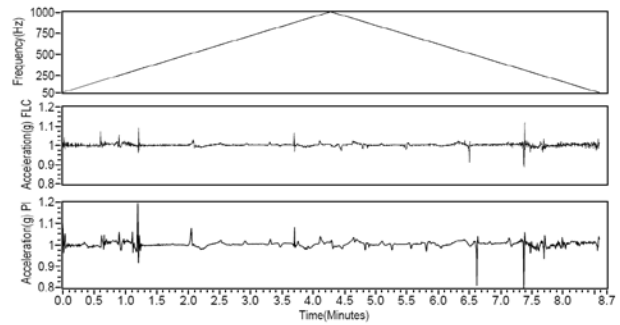


Fig. 24. Sine sweep response of the FLC for 1 octave/minute.

On the other hand the tracking error of 20% is maintained in PI control. For sweep test the acceleration waveform amplitude is recorded for every 1Hz frequency interval and the total sweep time of 8.64 minutes is used for 50Hz – 1 kHz – 50Hz cycle. This exercise again proves FLC to be adaptive to un-modeled dynamics of the vibration actuator.

## 5. CONCLUSION AND DISCUSSION

This paper has presented a model free fuzzy logic based intelligent time domain digital acceleration magnitude controller for sine vibration generation on an electrodynamic vibration actuator. The shaker is excited on waveform basis and the amplitude of the generated vibration is controlled using fuzzy PI and conventional PI control methods. Fuzzy logic control is derived from the classical PI technique and a practical procedure is presented to control a vibration actuator. Experimental results based on the tests conducted have demonstrated that this solution is capable of guaranteeing a good acceleration reference tracking and disturbance rejection as compared to conventional PI controller. Furthermore, a sine sweep test conducted has shown that fuzzy PI control produces tracking error of 10% as compared to 20% for conventional PI. Based on these initial

experimental results it can be concluded that fuzzy PI controller is a better solution to vibration actuator control as compared to the conventional PI control. However, performance comparison of these two controllers for further wide bandwidth actuators with complex non-rigid load dynamics needs to be investigated. Additional research in this line is currently being undertaken.

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**K.P.S Rana** received M.Sc. degree in Physics (specialization in Electronics) from Meerut University, Meerut, India in 1989 and M.Tech. degree in Applied Optics from Indian Institute of Technology Delhi, India, in 1991. He served Indian Space Research Organization (ISRO) from 1993 to 2000 as Scientist. Since August 2000 he has been with Netaji Subhas Institute of Technology (NSIT), Dwarka, New Delhi, India, as Assistant Professor at the Department of Instrumentation and Engineering. He has established a state-of-the-art instrumentation laboratory at NSIT. His current research and teaching interest includes PC based measurements, virtual instrumentation and intelligent instrumentation and systems.



Prof. R. Singh obtained B.Sc. Engineering (Mechanical) from Kurukshetra University, India, in 1978, M.Tech. from IIT Delhi, India, in 1980 and Ph.D. from University of Rajasthan, Jaipur, India, in 1986. He has been Principal of Govt. Engg. College, Bikaner, C.R. State College of Engineering, Murthal, Sonapat and Netaji Subhas Institute of Technology, New Delhi since 2004-2009. Presently he is Executive Secretary of Indian Society for Technical Education, New Delhi. His research interest includes interdisciplinary areas like Automation and Technology Management.



**Prof. K.S. Sayann** received B.E. degree in mechanical engineering from SVNIT, Surat, India, in 1968 and M.Tech. degree in design and production engineering from MANIT, Bhopal, India, in 1970 and Ph.D from IIT, Bombay, India in Mechanical engineering in 1977. Currently he is with Guru Teg Bahadur Institute of Technology, Guru Gobind Singh Indraprastha University, G-8 Area, Rajouri Garden, New Delhi - 110 0027, India as

Director. Prior to this he served MANIT, Bhopal, India as Director. His research interest includes power plant instrumentation and technology management.