Chapter 8

FUZZY CONTROL OF A PROTOTYPE EDVA

8.1 Introduction

In this chapter a fuzzy logic based digital sinusoidal acceleration waveform amplitude controller for an in-house developed prototype PC based Electrodynamic Vibration Actuator (EDVA) is presented. The Fuzzy Logic Control (FLC) purpose is to reproduce pre-defined sinusoidal acceleration amplitude at the vibration table of the EDVA. Sinusoid vibration profiles (sine and linear sine sweep) are considered for a closed-loop controlled vibration generation for rigid load as an initial exercise. 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 levels. 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 Proportional-Integral (PI) controller designed based on the direct synthesis concept. FLC is found to be fast responding and more robust to un-modeled dynamics of the shaker system. Furthermore, the implemented approach for FLC is simple, model free, straightforward and free from the un-modeled and complex dynamics of the vibration actuator system. The actuator design, FLC synthesis, FLC implementation using the LabVIEW software package with Fuzzy Logic Control add-on Toolkit and comparative study with a PI controller in real time are presented in this chapter.

8.2 Modern EDVA system
The 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 purposes. It comprises of three main components: a vibration exciter, a power amplifier and a digital control system. Figure 8.1 shows various components required for a closed-loop PC based controlled vibration generation. The vibration exciter transforms the electrical energy fed to it into physical movements, i.e. mechanical vibrations. The interface to the PC is two-fold. First, it is used for measurement of generated vibrations, and, secondly it also generates the base controlled signal for the power amplifier. Hence, in the PC controlled vibration actuators, the Data Acquisition (DAQ) device generates the base signal as per the desired profile in amplitude, frequency and time. It may be noted that the general purpose DAQ card used in the experiment under consideration is designed for ±10V and 4-20mA output ratings. The DAQ cards cannot directly drive the shaker requiring high armature current. On the other hand, the DAQ card being fully programmable, allows users to generate complex excitation waveforms and apply the intelligent digital controller which requires a lots of programming. This base signal is further amplified by the power amplifier to cater to the needs of the shakers for higher current requirements. The PC monitors the vibration test in real time. It guides the DAQ card for the required changes in the shaker excitation waveform amplitude so as to meet the target vibration profile.

Figure 8.1: Components of a computer controlled EDVA system.
The moving coil principle for vibration generation is almost universal in electrodynamic vibration actuators for vibration testing. As in the loudspeakers whose construction closely 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 [Fair & Bolton, 1993]. 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 test specimen is attached to the moving coil via a table assembly mounted using suspension mechanism. It is constrained to move vertically in to and fro motion. The control mechanism in the electrodynamic vibration actuator is achieved by controlling the voltage applied to moving coil. The other static field is 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 monitored for the active control implementation. A prototype PC based EDVA for laboratory education and research is developed as explained in the next section.

8.3 Design and analysis of a prototype EDVA

This section details the design, simulation and analysis of a prototype in-house developed electrodynamic shaker system.

8.3.1 Magnetic moment based analysis of EDVA

The moving coil EDVA works on the phenomenon of generation of alternating magnetic poles at the two ends of a coil excited by AC current source. Another coil excited by DC current behaves as a permanent magnet and hence an oscillating force is developed between fixed pole of permanent DC excited magnet and alternating pole of AC excited magnet when currents are
supplied to both the coils. In this research, analysis and modeling of the vibration actuator have been done considering the two coils, armature (AC) and permanent (DC), as two bar magnets each having its magnetic moment \( m \), depending on the electrical and physical parameters of the coil like excitation current, area of coil, length of coil and number of turns. The force between the two poles of two bar magnets is given by Eq. [8.1].

\[
f = \frac{\mu_0 m_1 m_2}{r^2} \text{ N} \quad \text{[8.1]}
\]

Where \( \mu_0 \) is the constant of magnetic permeability, and \( m_1 \) and \( m_2 \) are magnetic moments of the two coils and \( r \) being the instantaneous distance between the poles. Furthermore, magnetic moment of a pole is given by Eq. [8.2].

\[
m = N i A m^2 \quad \text{[8.2]}
\]

Where, \( N \) is the number of turns, \( i \) being the current supplied and \( A \) is the area of the pole as given by Eq. [8.3].

\[
A = \frac{\pi D^2}{4} \text{ m}^2 \quad \text{[8.3]}
\]

The fact, that the force between two magnets follows the inverse square law i.e. the force is inversely proportional to the square of instantaneous distance between the two bar magnets, is well taken care of to calculate the work done in generating the physical motion. As the distance between the two magnet keep changing due to the periodic motion of the armature magnetic pole hence net force can be calculated by the net work done. Work done by the moving coil for a distance \( dx \) at \( x \) separation is given by Eq. [8.4].

\[
dW = \frac{\mu_0 m_1 m_2}{x^2} \, dx \text{ J} \quad \text{[8.4]}
\]

Normally, the amplitude of vibration is of the order of few centimeters. Integrating the above function from \(-x/2\) to \(x/2\), net work done \( W \) can be achieved. Net force is calculated from the work done and hence acceleration, by knowing the mass of the table of the moving assembly.
8.3.2 Shaker design

A prototype computer in loop shaker system was designed and developed in house for the specifications listed in Table 8.1. The main aim for developing this shaker system was to have a workable computer controlled cost effective EDVA system for laboratory teaching and research applications. Low weight payloads were used as test objects for this in-house developed shaker system. The measurement and control activity was realized using the LabVIEW S/W along with the fuzzy logic toolkit.

Table 8.1: Design Parameters

<table>
<thead>
<tr>
<th>Physical Details</th>
<th>Electrical Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnet-</td>
<td>Electromagnet-</td>
</tr>
<tr>
<td>No. of Turns: 20800</td>
<td>Current: 100mA</td>
</tr>
<tr>
<td>Length: 45mm</td>
<td>Voltage: 129VDC</td>
</tr>
<tr>
<td>Inner Dia.: 68mm</td>
<td></td>
</tr>
<tr>
<td>Moving Coil-</td>
<td>Moving Coil-</td>
</tr>
<tr>
<td>No. of Turns: 160</td>
<td>Current: 3A(rms)</td>
</tr>
<tr>
<td>Length: 100mm</td>
<td>Thrust: 35N</td>
</tr>
<tr>
<td>Inner Dia.: 47mm</td>
<td>Resistance: 6Ω</td>
</tr>
<tr>
<td>Mass: 180grams</td>
<td>Acceleration: 5g</td>
</tr>
<tr>
<td></td>
<td>Frequency: 50-1kHz</td>
</tr>
</tbody>
</table>

8.3.3 Design analysis

Making use of the design data of the two coils as shown in Table 8.1 magnetic moment of the permanent magnet for 129mA current excitation comes out to be 9.74453 Am². Whereas, the armature coil magnetic moment due to its physical parameters is 0.277591 m² per Ampere. This yields the net work done between the two poles, considering 10mm separation, of 0.262848 Joules. Hence, the force calculated is 52.4696 N. Mass of the unloaded table is taken as 0.5 Kg. Thus, the acceleration achieved by the actuator comes out to be 105.139 m/s² or 10.6524g.

A computer program using LabVIEW platform was developed for modeling and simulation of the actuation system. User interfaces in terms of providing the coil parameters and mass of the
table were created. Output for the generated vibration, displacement and velocity of the table were plotted. Figure 8.2 shows the front panel of the developed LabVIEW code. Most interesting part has been the sinusoidal current excitation to the armature. It simulates the actual working model of the vibration exciter. The computed acceleration is further integrated to get the velocity of the vibrating platform. The acceleration data is also double integrated to get displacement plot for the vibrating platform. All the waveforms, seen as the tabs, on the front panel of the developed program, viz. current, acceleration in g units, velocity and displacement are displayed. This program has been useful tool to study the effects of the various parameters on the shaker design. Figure 8.4 shows the schematic of the developed electrodynamic vibration actuator system. Positioning of the moving coil and associated fixture table assembly was attended by means of a flexible suspension arrangement which constraints the movement to axial direction only and supports the weight of external payload. It may also be noted that the developed model, being approximate, does not take into account the flexible suspension system. Figure 8.5 shows the snap of the actual developed EDVA system.
Figure 8.3: Simulated movement of the armature coil.

Figure 8.4: Schematic of the EDVA system.

Figure 8.5: Developed prototype EDVA.
8.4 Acceleration waveform amplitude control

Figure 8.6 shows the closed loop acceleration waveform magnitude controller implementation scheme. As seen in Figure 8.6, the amplitude of the shaker excitation voltage waveform is continuously updated in a closed loop fashion to achieve the target acceleration waveform amplitude. \( r(k) \) and \( y(k) \) represent the reference and measured acceleration. Fuzzy Proportion-Integral (PI) and the conventional PI controllers are experimented and their performances are compared on the developed prototype shaker. Fuzzy PI controller was designed with the help of LabVIEW S/W and its fuzzy logic add on toolkit. Following are the design details of the two controllers followed by the real time implementation and comparison results.

![Control Scheme Diagram](image)

Figure 8.6: Acceleration waveform amplitude control scheme.

8.4.1 Fuzzy PI controller design

This section describes the details of various modules of fuzzy PI controller as defined in Eq. [4.2]. The controller was developed and implemented using LabVIEW S/W with fuzzy control add on toolkit software. Following are the controller details.

8.4.1.1 Fuzzification - For this experimentation, two fuzzy input variables are the error and the change of error. The inputs and outputs were 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. The quantization of the fuzzy variables was carried out in the normalized range of [-1, 1] for inputs as well as for output. The membership functions for e[k], Δe[k] and Δu_P[k] were all of the triangular types with 50% overlap as shown in Figure 8.7.

8.4.1.2 Rule base - The rule base for FLC can be imagined to be a two dimensional matrix as summarized in Table 8.2. The rows represent the various linguistic values that e(k) can take and columns indicate the various values of Δe(k). The entries in this matrix are the control action that has to be taken in the linguistic terms. The rule base was designed on the basis of the experimentally observed process reaction to the step change in the input reference [Lee 1990a; Lee 1990b]. Figure 8.8 shows the fuzzy surface formed by the various values of the two fuzzy inputs namely, e(k) and Δe(k) and the resulting incremental fuzzy output Δu_P[k].

![Triangular membership functions and fuzzy terms.](image)

8.4.1.3 Fuzzy inference engine – Mamdani’s min–max technique was been used as inference. 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 [Passino, 1993; Passino, 1996].

8.4.1.4 Defuzzification – This module converts the set of modified control output values into a single crisp value. Centre Of Gravity (COG) method for defuzzification 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 was used to defuzzify the fuzzy sets into a crisp control signal [Tang, Man, Chen & Kwong, 2001].

8.4.1.5 Fuzzy PI controller tuning - In this experiment the controller tuning has been done manually by optimizing the run time step response of the shaker acceleration amplitude. Overshoot and rise time parameters are considered as performance criterion for controller tuning. Since a comparative study with PI controller is also carried out both the controllers were tuned at 1 kHz.

<table>
<thead>
<tr>
<th>Error (e)</th>
<th>Change of error (Δe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB NB NB NB NB NM NS NS ZE PS PM PB</td>
</tr>
<tr>
<td>NS</td>
<td>NB NB NM NS NS NS ZE PS PM</td>
</tr>
<tr>
<td>ZE</td>
<td>NB NB NM NS ZE PS PM PB</td>
</tr>
<tr>
<td>PS</td>
<td>NM NS ZE PS PM PB</td>
</tr>
<tr>
<td>PM</td>
<td>NS ZE PS PM PM PB</td>
</tr>
<tr>
<td>PB</td>
<td>ZE PS PM PB PB</td>
</tr>
</tbody>
</table>

Table 8.2: Rule Base for Fuzzy PI Controller

Figure 8.8: Fuzzy PI controller control surface.
8.4.2 PI controller design using direct synthesis

Conventional PI controller has been used in some cases as acceleration amplitude controller [Chen & Liaw, 1999]. To obtain the desired specific response of the shaker system direct synthesis method of PI controller design was opted. Here, the process is identified and the controller parameters are accordingly chosen to meet the desired performance. This section describes the details. Comparative study of the proposed FLC was carried out with the conventional PI controller designed using the direct synthesis technique. The shaker acceleration waveform amplitude response is approximately expressed by a first order transfer function as shown in Eq. [8.5]. The structure of a PI controller algorithm implemented is given in Eq. [8.6].

\[
H_a(s) = \frac{\text{Response acceleration amplitude}(s)}{\text{Excitation voltage amplitude}(s)} = \frac{K_a}{\mu_a s + 1} \]  

[8.5]

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.

\[
G_a(s) = \frac{K_{AP} s + K_{AI}}{s} \]  

[8.6]

Before performing the controller design, the plant model \( H_a(s) \) is estimated from the measured step response. This is done by exciting the shaker at 1 kHz and varying the input excitation voltage in predefined steps. For 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 as shown in Eq. [8.7] [Chen & Liaw, 1999].

\[
H_{ad}(s) = \frac{1}{\mu_{ad} s + 1} \]  

[8.7]

The controller parameters of \( G_a(s) \) are therefore found to be as shown in Eq. [8.8],

\[
K_{AI} = \frac{1}{K_a \mu_{ad}}, \quad K_{AP} = \frac{\mu_a}{K_a \mu_{ad}} \]  

[8.8]
8.5 Performance criterion

For controlling the acceleration magnitude of the electrodynamic actuator system, the main performance evaluation criterions were the peak overshoot and the settling time. This is because in the vibration testing, the acceleration profile is defined for a given acceleration magnitude. In sine sweep test the actuator is required to maintain the desired acceleration amplitude throughout the sine sweep cycle. Minimizing the settling time would give faster acquisition of the desired profile. Furthermore, the minimization of the overshoot allows the device under test for precise acceleration limits. 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.

8.6 Experimental setup and results

This section explains the details of the experimental setup used to carry out the experiment. Results of some open-loop tests conducted to characterize the developed shaker and the used power amplifier on various parameters are 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 were required to know the capability and limits of the developed system. Figure 8.9 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 S/W with
add-on Sound and Vibration toolkit and Fuzzy Logic toolkit modules were used to develop a VI for carrying out the measurement and control objectives. Figure 8.10 shows the snap shot of the experimental setup developed.

Figure 8.9: Experimental setup.

Figure 8.10: Snap shot of the experimental setup.

Figure 8.11 shows the flowchart for the VI developed for measurement and control of the shaker. The front panel of the developed VI is shown in Figure 8.12. 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.

![Figure 8.11: Flowchart for EDVA control.](image)

A 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. The shear type accelerometer (Model 8704, ICP based, 4mA excitation, acceleration range ±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 1000 chassis and NI-SCXI-1530 accelerometer input module were used. Both input and output were 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 are transferred in the
blocks of 1600 samples. Hence the corrective action of the controller gets updated every 40ms. 40ms also happens to be the loop time. The timing aspect of FLC has also been studied. As compared to the PI controller, 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 100μs per iteration. It may be noted that this time is much smaller than the 40ms time for loop execution.

Figure 8.12: Front panel of the developed VI for acceleration magnitude control.

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 were also studied. The measured frequency response of the power amplifier is shown in Figure 8.13. 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 were conducted. The frequency response of the shaker is shown in Figure 8.14. As expected the two resonances are observed at around 20Hz and 1450Hz. The lower resonance at around 20Hz is attributed to the 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 Figure 8.15. As seen in Figure 8.15 the response to voltage variation is nearly linear. These studies have been very useful tools for estimating the capabilities of the experiment under consideration.

Figure 8.13: Measured frequency response of power amplifier.

Figure 8.14: Measured open-loop frequency response of EDVA (@2V).

Figure 8.15: Effect of voltage variation on EDVA response (@ 1 kHz).
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 were recorded and are shown in Figure 8.16. The dynamic model of the plant $H_a(s)$ was estimated using the parametric model estimation technique. The controller parameters were derived as mentioned earlier for time constant ($\mu_{ad}$) of 0.4s. Figure 8.17 shows the performance of the
estimated model, as can be seen the measured and the predicted performance are same, thus validating the model.

\[
H_a(s) = \frac{0.166}{0.4s + 1} \quad \text{[8.9]}
\]

\[
G_a(s) = \frac{6s + 15.00}{s} \quad \text{[8.10]}
\]

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 \( K_{UPI} = 2.8 \). Figure 8.18 shows the reference tracking performance of fuzzy PI and conventional PI controllers. At 1 kHz excitation, the reference acceleration magnitude was set for 1g and 2g alternatively several times and the response was 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 performances for both the controllers are obtained. Similar exercise was conducted at other end of frequency at 50Hz. Figure 8.19 shows the variation of the acceleration magnitude vs. iteration count. As seen in Figure 8.19 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 8.3 summarizes the comparison of the two control logics at these two frequencies. Estimation of overshoot, rise time and settling time was 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 produced a large overshoot of 16% as compared to 5.2% of fuzzy PI at 50Hz excitation, i.e., 67% more than fuzzy PI. Figure 8.20 shows the FFT result for FLC. As seen clearly, the frequency spectrum has a single peak of 2g at 1 kHz as expected.

Another similar exercise of reference tracking was done with small rigid load of 100grams. Figure 8.21 and Figure 8.22 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 performed better. Table 8.4 compares the results of two performances. It is noted that FLC again performs better than the PI. Disturbance rejection of the developed FLC was also investigated. For a reference acceleration of 1.5g a known disturbance of 0.5g was introduced and the tracking performance was studied. Figure 8.23 shows the time histories of the tracking performances under load of 100grams at 50Hz excitation. Here fuzzy PI responded faster with less overshoot. PI rejected the disturbance in 16 iterations against 9 iterations for fuzzy PI.

Figure 8.18: Fuzzy PI and PI controller step response results for bare table at 1 kHz.

Figure 8.19: Fuzzy PI and PI controller step response results for bare table at 50Hz.
Table 8.3: Acceleration Amplitude Tracking Performance Comparison for Bare Table.

<table>
<thead>
<tr>
<th>Excitation Frequency</th>
<th>Controller Type</th>
<th>Rise Time (Iteration)</th>
<th>Overshoot (%)</th>
<th>Settling Time (Iteration)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1kHz</td>
<td>Fuzzy PI</td>
<td>12</td>
<td>0.0%</td>
<td>16</td>
<td>FLC settles 15% faster</td>
</tr>
<tr>
<td></td>
<td>PI</td>
<td>13</td>
<td>0.0%</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>50Hz</td>
<td>Fuzzy PI</td>
<td>7</td>
<td>5.2%</td>
<td>17</td>
<td>FLC settles 15% faster</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>and overshoots 67% less</td>
</tr>
<tr>
<td></td>
<td>PI</td>
<td>6</td>
<td>16.0%</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8.20: Spectrum analysis (FFT) of the FLC controlled shaker output at 1 kHz.

Figure 8.21: Fuzzy PI and PI controller step response results for loaded table at 1 kHz.
Figure 8.22: Fuzzy PI and PI controller step response results for bare table at 50Hz.

Table 8.4: Acceleration Amplitude Tracking Performance Comparison for Loaded Table

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

Figure 8.23: PI and FLC performances for disturbance rejection.
To investigate the acceleration tracking performance in the entire frequency range of the prototype shaker from 50Hz-1 kHz, a linear sine sweep test under rigid load of 100 grams was conducted at the sweep rate of 1 octave/minute. The frequency was swept from 50Hz to 1 kHz and back to 50Hz at the specified rate. Figure 8.24 shows the result. As seen clearly the fuzzy controller maintains the error within a band of 10% in the full sweep cycle. On the other hand the tracking error of 20% is maintained in PI control. For sine sweep test, the acceleration waveform amplitude is recorded for every 1 Hz frequency interval and the total sweep time of 8.64 minutes was used for 50Hz – 1 kHz – 50Hz for one cycle. This exercise again proved FLC to be adaptive to un-modeled dynamics of the vibration actuator.

Figure 8.24: Sine sweep response of the FLC for 1 octave/minute.

8.7 Chapter summary

A systematic approach, for EDVA model development, based on magnetic moment is presented in this chapter. The approach can be extended to multi-degree of freedom vibration systems. The simplicity of the model enables a large number of trial designs to be examined with
ease. By examining the variations in device parameters, a designer can gain a good grasp of a shaker’s operation and critical design parameters. Sufficient information about the electrical design can be obtained from the above approach about the final instrumentation system to be realized. Theoretical to experimental differences are attributed to the quality of the suspension system used.

Furthermore, this chapter has presented a fuzzy logic based intelligent time domain digital acceleration magnitude controller for sine vibration testing on EDVA. The developed FLC required no prior system modeling for its implementation. The shaker was excited on complete waveform basis and the amplitude of the generated vibrations were controlled using fuzzy PI and conventional PI control methods. FLC was derived from the classical PI technique and a practical procedure was presented to control a vibration actuator. In this experiment, the FLC was implemented using off-the-shelf LabVIEW S/W toolkit for fuzzy logic implementation. The FLC was tuned manually by optimizing the step response of the EDVA. 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. The conventional PI controller was also implemented using the LabVIEW S/W of-the-shelf PID toolkit. The PI controller was designed using a direct synthesis approach of the controller design. In this approach the process is first identified and then the controller parameters are found for a desired step response performance of the closed loop process. Both the controllers were tuned for a given performance for the comparative study. Fuzzy PI controller was found to be outperforming the conventional PI in all the tests conducted. In all these tests, the rigid payload was used as test object. The tests were performed with and without the payload for some select excitation frequencies.

Furthermore, to investigate the acceleration tracking performance, in the entire frequency range of the developed prototype shaker from 50Hz-1 kHz, a linear sine sweep test under rigid load of 100grams was conducted at the sweep rate of 1 octave/minute. The frequency was swept from 50Hz to 1 kHz and back to 50Hz at the specified rate and the acceleration amplitude was recorded. It is found that the fuzzy PI controller produces tracking error of 10% as compared to 20% for
conventional PI. Based on these experimental results, it can be concluded that the fuzzy PI controller is a better solution to EDVA control as compared to the conventional PI control. Additionally, the implementation of FLC required no prior system information in contrast to PI control.