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FUZZY CONTROL OF A RESONANT VIBRATION DRYER

by

Vinay Sudera

A thesis

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Applied Science

in

Mechanical Engineering

RTETTE TO T

Toronto, Ontario, Canada, 2003

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Abstract

This thesis presents a fuzzy control method for a vibratory grain dryer. The proposed control method maintains the resonant condition for a dynamical system having constant linear stiffness, variable mass and variable damping coefficient. The MATLAB simulation results have confirmed that the fuzzy control method based on amplitude measurement is reliable and efficient. An experimental setup has also been developed to implement the proposed control method. Experimental results have demonstrated the effectiveness of the fuzzy control method.

Acknowledgements

The author is deeply indebted to his supervisors Prof. Shudong Yu and Prof. Guangjun Liu for their help, financial support, stimulating suggestions and encouragement throughout the graduate program.

The author would like to thank Mr. Roy Churaman, Mr. Joseph Amankrah, Mr. Allan Machin, Mr. Hamid Ghamei, Mr. Reg Michie and Mr. Andrew Heim of the Department of Mechanical, Aerospace and Industrial Engineering at Ryerson University, and Mr. Martyn Vanravenswaay of A-Tech Instruments Ltd., for their assistance in the experimental setup and valuable suggestions; also Mr. Vipul Shah, for his feedback during several meetings.

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Nomenclature

C	Damping coefficient (Ns/m)	
m	Eccentric mass (kg)	
e	Distance to mass center of the eccentric weights from rotational axis(m)	
f	Interactive force between bed and grains (N)	
t	Time (s)	
8	Gravitational acceleration (m/s ²)	
K	Spring constant or stiffness (N/m)	
$M \text{ or } M_{\mu}$	Mass of unloaded system (kg)	
M,	The total system mass (kg)	
NM	Negative medium	
NL	Negative low	
NVL	Negative very low	
NVVL	Negative very very low	
NZ	Negative zero	
PL	Positive low	
PM	Positive medium	
PZ	Positive zero	
PVL	Positive very low	
PVVL	Positive very very low	
X	Vibration amplitude (m)	
z	Dynamic displacement (m)	

ż	Dynamic velocity in vertical direction (m/s)
ΔA	Change in amplitude (m)
ΔA_n	Normalized amplitude change
A _{max}	Maximum amplitude (m)
A _{curr}	Current amplitude (m)
ΔV_i	Input voltage change (V)
ΔV_o	Required voltage change (V)
V_{\max}	Voltage corresponding to maximum amplitude (V)
V _{curr}	Current voltage being sent to motor drive (V)
V _{new}	New control voltage to be sent to the drive (V)
ω or ω_{op}	Operating frequency (rad/s)
ω_n or ω_{nf} (new)	Natural frequency of system (rad/s)
$\Delta \omega_o$	Equivalent defuzzified frequency change from fuzzy controller (rad/s)
ζ	Damping ratio
x _i	An element in the universe of discourse
$\mu(x_i)$	Membership grade of the element (x_i)
Δm	Reduction in overall system mass (g)
loop	Initializing variable
I	Index variable of "for" loop
abs(x)	Absolute value of x
ΔV_{oi}	i th voltage output from fuzzy defuzzification (V)
f_n	New natural frequency (Hz)
M _R	Required additional mass (kg)

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X – Axis	An axis formed by the right hand coordinate system			
Y - Axis	An axis parallel to the motor axis and positive in the direction as we move			
	from front to back of the motor			
Z – Axis	An axis in the vertical direction and positive in the upward direction			
Ι	Rotational inertia (kg/m ²)			
θ	Angle of pendulum (rad)			
R	Length of pendulum (m)			
m _b	Mass of pendulum (kg)			
I _{CG}	Center mass moment of inertia (kg/m ²)			
d	Distance between two parallel axis (m)			
Iparallelaxis	Mass moment of inertia around an axis parallel to the axis passing through			
	C.G (kg/m ²)			
Δy	Distance between mass center of flat and previous C.G. in y-axis (m)			
ΔΥ	Distance between new C.G. and previous C.G. in y-axis (m)			
Δz	Distance between mass center of flat and previous C.G. in z-axis (m)			
ΔZ	Distance between new C.G. and previous C.G. in z-axis (m)			
Δx	Distance between mass center of flat and previous C.G. in x-axis (m)			
ΔΧ	Distance between new C.G. and previous C.G. in x-axis (m)			
I _{xx}	Mass moment of inertia around X-axis (kg/m ²)			
I _{yy}	Mass moment of inertia around Y- axis (kg/m ²)			
θ_1	Dynamic angular displacement of bed measured from static equilibrium,			
	in YZ plane (rad)			
$\dot{ heta}_1$	Angular velocity of bed, measured in YZ plane (rad/s)			

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θ_2	Dynamic angular displacement of bed measured from static equilibrium				
	in XZ plane (rad)				
$\dot{ heta}_2$	Angular velocity of bed, measured in XZ plane (rad/s)				
l_1	Distance between C.G. and front guide rail measured in YZ plane (m)				
<i>l</i> ₂	Distance between C.G. and back guide rail measured in YZ plane (m)				
l ₃	Distance between C.G. and left guide rail measured in XZ plane (m)				
l ₄	Distance between C.G. and right guide rail measured in XZ (m)				
L	The Lagrangian variable (kgm ² s ⁻²)				
Τ	Kinetic energy of system $(kgm^2 s^{-2})$				
U	Potential energy of system $(kgm^2 s^{-2})$				
[<i>M</i>]	Mass matrix (kg)				
[K]	Stiffness matrix (N/m)				
<i>W</i> _{ni}	i^{th} natural frequency of system, $i = 1, 2, 3$ (rad/s)				

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CHAPTER 1 INTRODUCTION

1.1 Introduction

The purpose of introducing vibration to a drying bed and maintaining it at a significant level is to fluidize the grains in the drying chamber, and to promote the heat transfer between the grains and the hot air blown into the drying chamber. Vibration-induced fluidization may improve the drying efficiency of a manually controlled resonant vibration drier two fold [1].

To fluidize the grains and enhance drying efficiency, the peak vertical acceleration of the vibrating bed should be significantly larger than the gravitational acceleration while the displacement amplitude is maximized. To achieve the required level of acceleration and displacement amplitude for fluidization, the concept of resonance is utilized. At resonance, the vibration amplitude peaks. This, coupled with the excitation frequency (or motor speed), produces a desired value of acceleration.

1.1.1 Plant and Modeling

The plant under control is a vibratory grain dryer, shown in Fig. 1.1. The plant consists of a container with Lucite walls and perforated pegboard base, attached to the base plate. The motor is coupled to the Lucite container through angles. The vibration is produced by the two eccentric weights, mounted on two gears rotating at the same speed but in opposite directions. The eccentricity of the two counter rotating weights is equal. This causes only a vertical force to be transmitted to the pegboard. Furthermore, the bed is constrained to move in the vertical direction by guide rails.

The grains are vibrated while hot air is introduced to the base of the drying bed. Ambient air is drawn through a heater by a centrifugal fan and discharged at the base of the perforated pegboard.



Figure 1.1 Major parts of vibrating drier

1.1.2 Problem Statement

The resonance amplitude is a function of stiffness, damping coefficient, drying system mass, excitation frequency and excitation amplitude. The natural frequency depends on the system mass and stiffness. The system mass depends on the initial state of system and time (due to drying). For a given initial amount of wet grains, the equivalent mass added to the system from the grains is different for different types and moisture content of the grains. The equivalent mass is a function of the grain size, geometry and moisture. Damping in the system is a combination of damping from the springs, and losses due to friction. The damping coefficient is also different at different times for a given grain type. The drying system is complex for an exact analysis. Thus, it is beneficial to develop an intelligent control to run the system at the optimized motor speed. In this work, a fuzzy control method is developed to automatically run the drying system at resonance. Computer simulations and experiments are conducted to investigate the effectiveness of the proposed method.

1.2 Motivation for Intelligent Fuzzy Control

'Conventional control techniques such as Proportional Integral Derivative (PID) control have many advantages. When values of controller parameters are known, control signals are generated exactly. If a process can be modeled mathematically, many of these techniques may provide good stability, robustness and speed of response. However, there are several disadvantages associated with the conventional control methods. The control algorithms are "hard" or "inflexible", and cannot generally handle "soft" or "flexible" intelligent control.

The ever-increasing technological demands call for complex systems to achieve high performance. Some complex systems cannot be controlled in a conventional manner because of vague knowledge of a process. Acquisition of adequate system knowledge is often problematic due to system complexity, variable parameters, load uncertainty, etc. To control complex systems, intelligent control techniques are often used.

The area of intelligent control is a fusion of many research areas. Generally, intelligent control involves learning, reasoning and inference, making use of incomplete, vague, non-crisp and qualitative information, past experience and knowledge. Intelligent control systems are

able to perform one or more of the following functions: planning actions at different levels, learning from past experience, identifying failures that threaten system behaviors and reacting appropriately, etc. These functions define the areas of planning and expert systems, fuzzy systems, neural networks, machine learning, and failure diagnosis [2].

Fuzzy logic control is a subset of intelligent control. The main feature of fuzzy control is that a control knowledge base is available within the controller; the control actions are generated by applying existing conditions or data to the knowledge base, making use of an inference mechanism. The knowledge base and the inference mechanism can process non-crisp and incomplete information. The main idea behind fuzzy control is to model an expert operator, who is able to control the process, instead of using a mathematical formalization of the process. Fuzzy control has been successfully used in areas where workable mathematical models for plants are very difficult or impossible to derive. There is a simple language difference between fuzzy and conventional control. Ordinary differential equations are the language of conventional control while rules are the language of fuzzy control.

1.3 Literature Review

A few successful applications of fuzzy control are reviewed. Due to long time delay and other nonlinear factors associated with the plant and drying process, use of classical feedback controllers will encounter difficulties in controlling the grain dryers [3]. It is difficult to model the interactions between the grains and the bed. Fuzzy control has been successfully used for implementing human reasoning and does not rely on a precise system dynamic model. Experienced operator knowledge can be represented in terms of fuzzy qualitative variables. In fact, it gives the most efficient knowledge representation method for rule-based systems dealing with continuous variables [4]. A fuzzy controller is able to deal with significant

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variations in the input fields [5]. A hybrid fuzzy PID controller is used to maintain the output product moisture at a required level for a nonlinear, time variant and significant time lag industrial steam heated dryer [6]. A fuzzy logic controller provides a highly efficient solution for a multi-variable control problem. Fuzzy logic can be used to design supervisory controllers from operator experience and experimental results [7]. In crane control, the sway must be reduced to almost zero for load release. Fuzzy control was successfully designed, based on operator experience, and tested for the anti-sway control of cranes [8]. Fuzzy control, in comparison with a conventional controller, has faster response time and significantly smaller overshoot [9]. A fuzzy-PID controller, for a nonlinear and time variant naphtha hydrodesulfurizing petrochemical plant, was able to control top temperature, for both steady and transient system states [10]. A fuzzy controller and a proportional-plus-derivative controller are used for controlling a servo motor, flexible arm and a system with three vibration modes. The system response shows that the fuzzy controller not only has all the functions of a proportional-plus-derivative controller but also performed better than the proportional-plusderivative controller when nonlinearities and uncertainties are introduced [11]. Fuzzy control of a waste incineration plant is investigated in [12, 13], and digging track of an experimental excavator is investigated in [14].

There are other applications where fuzzy control has been effectively used. Even if a controller can be designed using the conventional analytical theory, a designer may still prefer to use the non-analytical approach because (i) a fuzzy controller is easy to design; (ii) it may be easy to implement in hardware; and (iii) it may result in a more robust controller (A robust controller is less susceptible to system parameter changes or to noise.) [15]. Knowledge about a dynamic system that definitely cannot be expressed in any mathematical way may be

expressed in rule bases. Fuzzy logic provides the best technique for knowledge representation that could be devised for encoding knowledge about continuous variables [16]. The ease with which a priori linguistically expressed information may be incorporated into a fuzzy system, gives the approach a potential advantage concerning the use of additional cost functions in the adaptive process [17].

Because of the lack of mathematical models, the stability of a fuzzy system can only be described qualitatively without quantitative indices [18, 19]. Comparisons among different control methods are given in Table 1.1, the principal contributions of fuzzy systems, neural networks, and genetic algorithms are complementary rather than competitive [20].

	Fuzzy Systems	Neural Networks	Genetic Algorithms	Conventional Control Theory
Mathematical model	SG	В	В	G
Learning ability	В	G	SG	В
Knowledge representation	G	B	SB	SB
Expert knowledge	G	В	B	SB
Nonlinearity	G	G	G	В
Fault tolerance	G	G	G	· B
Uncertainty tolerance	G	G	G	В
Real-time operation	G	SG	SB	G

 Table 1.1 Comparison of Control Methodologies [20]

Note: G stands for "good"; SG stands for "slightly good"; B stands for "bad"; SB stands for "slightly bad".

The formulation of fuzzy models consists of three basic sub-problems: structure identification (input variables, membership functions and fuzzy rules), parameter estimation (determination of unknown parameters), and model validation (testing) [21]. From its conception to present state, fuzzy research has advanced towards more intelligent systems. Development of fuzzy systems started with manual tuning of system parameters based on observing the system performance. In the 1980's, Takagi and Sugeno developed an algorithm

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for constructing fuzzy rules using training data [22]. Development of both neural networks and fuzzy logic in the 1980's gave impetus to the use of neural network learning techniques for identifying parameters in a fuzzy system [23]. In the 1990's, optimization of fuzzy system parameters was done using genetic algorithms [24]. Currently, researchers are working on a new generation of intelligent systems or hybrid systems, using genetic algorithms, artificial neural networks, fuzzy logic and other artificial intelligence techniques [25, 26]. NEFGEN (Neuro Fuzzy Generator), ANFIS (Adaptive-Network-based Fuzzy Inference Systems), NEFCON (Neuro-Fuzzy Control), NEFCLASS (Neuro-Fuzzy Classification) and NEFPROX (Neuro-Fuzzy Function Approximation) and other hybrid NF (Neuro-Fuzzy) adaptive network models are successfully tested [27]. These models differ in the way that learning is carried out, the kind of knowledge to be extracted and the nature of parameters of the derived fuzzy systems.

1.4 Contributions

There are three major contributions of this thesis work:

- 1. A fuzzy controller is developed;
- 2. The proposed fuzzy controller is successfully simulated using Matlab; and
- 3. Hardware instrumentation was implemented and tested successfully.

1.5 Organization of Thesis

In Chapter 2, redesigning of the drying system is discussed and then analysis is performed to measure mechanical properties and to formulate vibration equations. The system was redesigned for proper operations of a vibratory grain dryer. Details are given in Appendix A. Experiments were performed to determine the center of gravity and moment of inertia. Details are given in Appendix B. The Lagrange method was used for establishing vibration equations for the empty system with three degrees of freedom (details are given in Appendix C).

The steps for the fuzzy controller design are discussed in Chapter 3. Initial steps of a fuzzy logic controller involved choosing inputs and outputs, assigning membership function for the inputs and outputs, and forming fuzzy rules. Fuzzy rules represent partially the operating knowledge and system behavior. Simulations of the proposed fuzzy controller are done using Matlab.

Chapter 4 is divided into two parts. The first part discusses hardware instrumentation and programming details. The second part discusses the result of experiments conducted for the empty and loaded system under various conditions of grains and their types.

Chapter 5 concludes the thesis and discusses future work.

CHAPTER 2 MECHANICAL MODIFICATION AND VIBRATION ANALYSIS

2.1 Introduction

To fluidize grains and enhance drying efficiency of a vibration dryer, the effective bed acceleration in the vertical direction should be significantly (actual value depends on the amount and state of grains) larger than the gravitational acceleration (g). At resonance, for a single degree of freedom system with damping, local maximum acceleration and global maximum displacement amplitude take place simultaneously.

2.2 Mechanical Modification

The system response is dependent on the motor speed, which in turn depends on the control voltage (0-8.25 volts) being supplied to the motor drive. It was visually confirmed that the original system amplitude does not increase with the increasing control voltage beyond the maximum value. Theoretically, at lower or higher frequencies, displacement amplitude is lower than the resonant displacement amplitude. A Visual Designer program was written to study the system response over the complete frequency range; details of the program are given in Appendix A.

The motor frequency could not increased beyond 22 Hz (1320 r.p.m), as the motor drive goes into a saturation state. At 22 Hz, the motor withdraws 90 volts and 0.5 Ampere from the motor drive before machine modification. The machine was modified as shown in Fig. 2.1 with a detailed description given in Appendix A. The motor can reach 1800 r.p.m rotational speed after the modification of the machine.

2.3 Vibration analysis

The center of gravity (C.G.) is the point at which the entire mass of machine is considered



Figure 2.1 Modified machine

to be located for the purpose of understanding the system motion. The C.G. was required for calculating moment of inertia and to measure distances between C.G. and line of force. Experiments were performed to determine the C.G. and moment of inertia. Details are given in Appendix B. The moment of inertia and the distances are used to formulate Lagrange equations. Initially, vibration analysis was done for a three degree-of-freedom analysis as given in Appendix C. In this section, only a one degree-of-freedom analysis is done.

The equation of motion of the vibrating bed under rotating eccentric weights is written as

$$M_t \ddot{z} + C\dot{z} + Kz = 2me_{\omega}^2 \sin(\omega t) + f$$
(2.1)

where M_t is the total system mass; C is the effective damping coefficient of the system; K is the system stiffness; z is the instantaneous vertical displacement amplitude; m is the mass of each eccentric weight; e is the eccentricity of each eccentric weight; ω is the rotational speed of the motor; f is the effective force acting upon the vibration bed.

For convenience, Eqn. (2.1) is normalized with respect to the total equivalent system mass. The desired standard equation of motion for a single degree-of-freedom system is then written as

$$\ddot{z} + 2\zeta \,\omega_n \,\dot{z} + \omega_n^2 \,z = \frac{2me}{M_*} \,\omega^2 \sin(\omega t) + \tilde{f} \tag{2.2}$$

where ζ is the effective damping ratio of the system; ω_h is the natural frequency of the system; \tilde{f} is the interactive force between the bed and grains normalized with respect to the mass of the empty system.

In general, the effective interactive force between the bed and grains is dependent on a number of factors such as the motion of the bed, the average grain size, the moisture, the degree of fluidization, etc. It is extremely difficult to develop a reliable mathematical model for the interactive force. Even if empirical model may be devised, it is deemed to be a complex one for which an analytical solution cannot be easily obtained. It is difficult to apply conventional control methods. This is why fuzzy control is highly desirable and used in this thesis. A steady state solution to Eqn. (2.2) may be easily obtained for the no-load situation. It is written as

$$z = X\sin(\omega t - \phi)$$

where the vibration amplitude, X, is given by

$$X = \frac{2me}{M_{t}} \frac{(\omega/\omega_{n})^{2}}{\sqrt{(1 - (\omega/\omega_{n})^{2})^{2} + (2\zeta\omega/\omega_{n})^{2}}}$$
(2.3)

A frequency response curve depicting the change of vibration amplitude with the excitation frequency is shown in Fig. 2.2.



Figure 2.2 Amplitude response curves

The operating or excitation frequency is the controlled variable. The main objective of the controller is to keep the operating frequency in the vicinity of the resonance frequency so that the response of the vibrating bed is at maximum.

CHAPTER 3 FUZZY CONTROL DESIGN

3.1 Introduction

For efficient heat transfer, the grain surface area in contact with the hot air should be maximized at all times. Thus, the instantaneous bed acceleration should be greater than the gravitational acceleration for a significant portion of time during one cycle to achieve the fluidization effect. Since the peak acceleration of the system is designed to be well above the gravitational acceleration for the plant, the objective of the controller is to achieve and maintain the resonant condition in order to optimize the energy use and drying time.

A loaded system natural frequency tends to be lower than the empty bed natural frequency. The loaded system natural frequency increases as grains are being dried with time. At startup, the operating frequency is set to be slightly greater than the natural frequency of the empty system. Subsequently, the fuzzy logic determines the first voltage change according to the set initial values of voltage change and normalized amplitude change, i.e., amplitude change normalized with respect to the current maximum amplitude. After the startup, the fuzzy logic determines the required voltage change according to the real measurements of voltage change and the corresponding normalized amplitude change. The Visual Designer program is written and used for data acquisition, processing and control. The fuzzy logic toolbox of the Matlab is used for fuzzy logic implementation.

3.2 Fuzzy Logic Control

Fuzzy logic control (FLC) provides a formal methodology for representing and implementing a human operator's knowledge about how to control a system. Generally, real world measurements and output values are crisp. General steps in designing a fuzzy logic controller involve assigning membership functions to the crisp inputs and outputs, and generating knowledge or rule base according to the human operator's experience. Real-time operations of fuzzy control start with the fuzzification of crisp input measurements. Then the inference engine determines which output rules are on at an instant. In the last operation, the output rules are defuzzified to a crisp value as illustrated in Fig. 3.1.



Figure 3.1 Crisp input and output for fuzzy control

In Fig. 3.1, $\Delta A = A_{curr} - A_{max}$, is the amplitude change; $\Delta V_i = V_{curr} - V_{max}$, is the input voltage change; ΔV_o is the required voltage change; A_{max} is the maximum amplitude; A_{curr} is the current amplitude; V_{max} is the voltage corresponding to maximum amplitude; V_{curr} is the current voltage sent to motor drive.

The fuzzy controller shown in Fig. 3.1 has four main components as follows:

 The "rule base" holds the knowledge in the form of a set of linguistic control rules that may contain fuzzy variables as conditions and actions. In general, the representation of fuzzy variables depends on the nature of a universe of discourse. A universe of discourse contains all elements of a variable space for a given problem. The membership functions for input (conditions) and output (action) variables have to be chosen for effective control. The rule base array is formed from the linguistic control rules and membership functions.

- 2. The fuzzification interface simply modifies the inputs (crisp to fuzzy sets) so that they can be interpreted and compared to the rules in the rule-base.
- 3. The inference mechanism evaluates which linguistic output rules are relevant at the current time, using the compositional rule of inference.
- 4. The defuzzification interface converts the linguistic output rules as determined by inference mechanism to a crisp output value.

3.3 Amplitude Control Method

In this section, an amplitude-based fuzzy controller is developed to achieve and maintain resonance conditions for a dynamic system having linear stiffness, varying mass and damping. Fuzzy model identification consists of three basic sub-problems [21]:

- 1. Structure identification involves finding the input and output variables; assigning membership functions to these variables; and determining the number of fuzzy rules comprising the underlying model.
- 2. Parameter estimation involves the determination of unknown parameters in the model using some optimization method based on both linguistic information obtained from operating experience and the general response of the actual physical system. Structure identification and parameter estimation are interwoven, and either of them cannot be independently identified without resort to another.

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Model validation involves testing the model based on some performance criteria,
 e.g. accuracy. If the model does not pass the test, then the structure has to be redefined and parameters have to be estimated again.

This methodology is used for estimation of parameters and designing of the fuzzy control. The operators used are listed in Table 3.1.

	Fuzzy Operator	Function
1	And	Minimum
2	Or	Maximum
3	Implication	Minimum
4	Aggregation	Maximum
5	Defuzzification	Centroid

Table 3.1 Fuzzy Operators and Their Functions

3.4 Controller Input and Output

The controller input and output are chosen to mimic the operator behavior. The motor frequency can be varied by varying the control voltage being supplied to its motor drive. In manual operations, the operator changes the motor frequency through the control voltage and then observes the system amplitude. This procedure is repeated until the maximum amplitude is achieved. The chosen inputs to represent the system behavior are:

1. ΔV_i is the voltage change (indirectly controls the motor frequency).

2. ΔA_n is the corresponding normalized amplitude change (section 3.4.1).

The system response depends on the motor frequency. The motor frequency is a linear function of the control voltage (0 - 8.25V) being supplied to the motor drive. Thus, an output chosen to control the system is the required control voltage change, ΔV_o , to be sent to motor drive.

3.4.1 Normalization

Normalization maps the physical values of the current process state variables into a normalized universe of discourse (normalized domain). Crisp amplitude input change divided by current maximum amplitude, i.e., $\Delta A / A_{max}$, is the normalized input to the controller.

3.5 Fuzzification

Fuzzification is related to the vagueness and imprecision in a natural language. It is a subjective valuation, which transforms a measurement into a valuation of a subjective value. Hence, it could be defined as a mapping from an observed crisp input space to fuzzy sets in certain input universes of discourse. Fuzzification plays an important function in dealing with uncertain information which might be objective or subjective in nature.

In this application, the observed data are crisp. Since data manipulations in a fuzzy logic controller are based on fuzzy set theory, fuzzification is necessary during an earlier stage. The choice of membership functions for each linguistic variable must be performed. This can be done by classification of the control input and output into classed fuzzy sets as shown in Figs. 3.2-3.4. Parameters are adjusted until satisfactory performance is achieved. The membership functions are divided between negative and positive universe of discourse, for efficient decision making.

Triangular membership functions are used for fuzzification of crisp measurements. Triangular membership functions were tested during simulations using the Matlab fuzzy toolbox. The triangular membership functions gave satisfactory response, and are used for voltage change (input and output) and normalized amplitude change as shown in Figs. 3.2-3.4.

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Figure 3.4 Membership function for voltage change (output)

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3.6 Knowledge Base

The knowledge base of a fuzzy logic controller is comprised of a database and fuzzy control base. Database concepts are used to characterize linguistic control rules and a fuzzy data manipulation. The fuzzy control base characterizes the control goals by means of a set of linguistic control rules. It should be noted that the correct choice of the membership function plays an essential function in a successful application. The representation of uncertain information with fuzzy sets brings up the problem of quantifying such information.

Fuzzy sets represent the meaning of the linguistic variables of the input and output variables. Six fuzzy sets are used for both inputs; and eight fuzzy sets are used for the output.

A fuzzy system is characterized by a set of linguistic control statements. It is in the form of "IF-THEN" rules. These rules are easily implemented by fuzzy conditional statements. In fuzzy logic, the collection of fuzzy control rules that are expressed as fuzzy conditional statements forms the rule set. The proper choice of input and output variables is essential to characterize the operation of fuzzy system.

At resonance, the vibrations amplitude is significantly higher than non-resonant conditions. This fundamental characteristic is used for designing the rule base. Consider any general vibration response, Fig. 3.5. At any instant t, assume that the operating frequency corresponds to state 1, Fig. 3.5; and the state 1 amplitude and control voltage values are stored in the maximum amplitude and the maximum control voltage variables, respectively. Next possible operating frequencies are states 2, 3, 4 and 5. The controller program changes the operating frequency from state 1 such that the system state becomes either 2 or 3; the amplitude change and the voltage change are positive for these states with respect to state 1. The state 2 or 3 amplitude is greater than the state 1 amplitude, therefore the maximum amplitude and the

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maximum voltage variables are set to state 2 or 3 amplitude and voltage values, respectively. Thus the rule is "If the voltage change and the amplitude change are positive, then the required voltage change is positive".

Similarly consider that the controller program changes the operating frequency from state 1 such that the system state becomes either 4 or 5; the amplitude change is negative for these states; and the voltage change for state 4 is positive and state 5 is negative with respect to the state 1. The maximum amplitude and the maximum voltage variables initial status remains (state 1) because the state 4 or 5 amplitude is lower than the state 1 amplitude. The rules are "If the amplitude change is negative and the voltage change is negative (state 5), then the required voltage change is positive" and "If the amplitude change is negative and the voltage change is negative.

Similarly consider that the controller program changes the operating frequency from state 4 such that the system state becomes 2; the amplitude change is positive and the voltage change is negative for this transition. The maximum amplitude and the maximum voltage change are set to the state 2 from state 4 because the state 2 amplitude is greater than state 4. The rule is "If the amplitude change is positive and the voltage change is negative, then the required voltage change is negative".

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Figure 3.5 General frequency response curve

The fuzzy rule base based on the above fundamental is given in Table 3.2.

ΔA_n	NM	NL	NZ	PZ	PL	PM
ΔV_i						
NM	PVL	PM	PL	NVL	NM	NVL
NL	PVL	PL	PVL	NVL	NL	NVL
NZ	PVVL	PVL	PVVL	NVVL	NVL	NVVL
PZ	NVVL	NVL	NVVL	PVVL	PVL	PVVL
PL	NVL	NL	NVL	PVL	PM	PVL
PM	NM	NM	NL	PL	PL	PVL

Table 3.2 Fuzzy Rules or Knowledge Base

where, NM - Negative medium; NL - Negative low; NVL - Negative very low; NVVL -Negative very very low; NZ - Negative zero; PL - Positive low; PM - Positive medium; PZ -Positive zero; PVL - Positive very low; PVVL - Positive very very low

Some examples include "If ΔA_n is NM and ΔV_i is NL then ΔV_o is PVL"; "If ΔA_n is NL and ΔV_i is NL then ΔV_o is PL." The control surface for Table 3.2 is shown in Fig. 3.6.

3.7 Defuzzification

As the control action must be a crisp value, the relevant output rule of the FLC is converted by the center of gravity method into a single crisp value using the following equation:



Figure 3.6 Control surface

$$\Delta V_{o} = \frac{\int_{i=1}^{n} \mu(x_{i})^{*} x_{i}}{\int_{i=1}^{n} \mu(x_{i})}$$
(3.1)

where, *n* is the number of discrete values on the universe of discourse; $\mu(x_i)$ is the membership grade of the element x_i in the universe of discourse.

The defuzzified output is added to the current maximum voltage and then the result is sent to the motor drive i.e.,

$$V_{new} = V_{\max} + \Delta V_o \tag{3.2a}$$

$$or \\ \omega_{new} = \omega_{max} + \Delta \omega_a$$
(3.2b)

where, V_{new} is the new control voltage to be sent to the drive; V_{max} is the stored control voltage

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at which maximum amplitude occurs. It is noted that the control voltage V_{max} can be V_{new} or V_{max} depending upon whether the amplitude change is positive or negative, respectively; ω_{new} is the new operating frequency corresponding to V_{new} ; ω_{max} is the operating frequency at which maximum amplitude occurs and $\Delta \omega_o$ is the equivalent defuzzified frequency change from fuzzy controller.

3.8 Heuristic Stability and Rules

Heuristic rules establish an outer boundary for the fuzzy output and enforces the controller stability. Thus, heuristic rules check that operating space converges i.e., the current output of fuzzy logic is not greater than previous output of the controller. If the current output is greater than the previous output, the current output is neglected and the previous output is increased or decreased, according to the amplitude change and voltage change, by 0.01 V. The heuristic rules acts as a supervisor for the fuzzy controller output. In addition, if the normalized amplitude difference is greater than 0.8, then the search space is reduced by half. This is so because there is a large variation in amplitude at resonance. Finally, if output from controller is within the range of (-0.006, 0.006) then the output is reduced to zero.

3.9 Simulation Results

The main objective of simulations is to determine whether amplitude based control can keep the operating frequency in the vicinity of varying natural frequencies for a dynamical system. Eqn. (3.3) simulates the loss of moisture with time. Table 3.3 presents the loss of system mass through evaporation taken at four different times [1].

Based on the measurements, a cubic polynomial, which gives mass reduction as a function of time t, is written as

where, t is the time in minutes, Δm is the reduction in overall system mass in grams.

	Mass Evaporated (g)	Time (Minutes)	
1.	0	0	
2.	12.5	5	
3.	26.0	15	
4.	. 33.5	25	

 Table 3.3 Evaporated Mass vs. Time

The effective damping-coefficient is different not only for different grain types but also at different times for a given grain type. The following linear equation is used for representation of the damping ratio.

$$\zeta = 0.0002835t + 0.081 \tag{3.4}$$

The simulation results shown in Fig. 3.7 show that the fuzzy control is effective. Amplitude control has open space convergence or has qualitative knowledge, i.e., maximum amplitude should occur. The flow chart for Matlab program is given in Fig. 3.8. In the flow chart, loop is the variable used for initializing; I is the index variable of "for" loop.





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Figure 3.8 Simulation flow chart

CHAPTER 4 EXPERIMENTS

4.1 Preparation for Experiments

4.1.1 Hardware Instrumentation

The vibration drier was previously interfaced with a computer only for data acquisition and analysis. To complete the control loop, the computer output was interfaced with the motor drive. Since the Visual Designer high speed analog output block can output non-isolated 0-10V or \pm 10V analog voltage, a simple visual diagram program was written and the non-isolated voltage (0-10V) was measured at a terminal board. The next step was to make the motor drive controller (KBMW120) compatible with the computer output voltage. Because the motor control drive requires isolated 0-10V DC analog voltage, a module is required to convert a non-isolated voltage to an isolated voltage. After system analysis and market search were done, a 5B-SCM5B49-05 voltage output module, a connector and a coaxial wire were procured for achieving signal isolation.

Terminal board jumpers J1, H17 are connected; jumpers J2, H18 are disconnected. The 5B isolation module is connected to channel 7 of the terminal board, which is equivalent to channel 1 of the high speed analog output module block in the Visual Designer program. The coaxial wire is connected to terminals "+" and "-" of the terminal board. The potentiometer is disconnected from the motor drive control. The motor drive control terminals "P2" and "F-" are connected to terminals "+" and "-", respectively, through the coaxial wires. This completes the hardware requirements and interfacing. The completed experimental setup is shown in Fig. 4.1.

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4.1.2 System Calibration

Calibration of the whole system was done using a Dytran portable shaker. Results of the calibration are given in Table 4.1. The sensitivity for the experimental setup is 0.10g/mV, i.e., if an Fast Fourier transform (FFT) analysis gives a peak value of 1 millivolt, then the system peak acceleration is 0.1 g, where g is the gravitational constant (9.81 m/s²).

	Peak Values	Frequency (Hz)
Shaker input	2.07g (Acceleration)	100
Setup FFT output	0.02 volt	100

Table 4.1 Calibration Data

4.1.3 Motor Calibration

The motor calibration was done by measuring the drive voltage and the motor speed in Hz at an increment of 0.1 volt in the meaningful range of 4-8 volts. Results are shown in Fig. 4.2.



Figure 4.2 Calibration of motor frequency

4.1.4 Placement of Accelerometer

The mechanical system has three degrees of freedom as explained in Appendix C. It can be concluded that at the second mode is decoupled i.e., the machine vibrates with one degree-offreedom and the other two modes are coupled. The translation mode is predominant for mode 1. As the controller is primarily concerned with the translation motion, the accelerometer is placed near the node for θ_I to capture the vertical bed acceleration.

4.1.5 Peak Acceleration

Time domain signals contain external, analog to digital conversion, and other noises. These signals are analyzed to the frequency domain using the FFT. In the frequency domain, acceleration at the motor frequency is significantly higher as compared to the acceleration due to the noise. This characteristic is used for getting the peak acceleration value from the frequency domain signal.

4.2 Programming

At startup, a pulse of 5 volts is sent to the motor drive. The eccentric weights produce a sinusoidal excitation. The vibration signal is acquired and analyzed. The Visual Designer program, Fig. 4.3, calculates the amplitude and voltage change, and then sends these values to an Excel worksheet. Matlab program, Fig. 4.4, reads the amplitude and voltage changes from the Excel worksheet and fuzzifies the crisp inputs. Then, the fuzzy inference engine determines which output rules are on, and defuzzifies the output rules to a crisp output. The heuristic rules check the stability of the fuzzy output. The Visual Designer program reads the crisp output and updates the motor drive control voltage, accordingly. In Fig. 4.3 and 4.4, abs(x), is absolute value of x; ΔV_{oi} , is the ith current output from fuzzy defuzzification; $\Delta V_{o(i-1)}$, is the previous output from fuzzy defuzzification.



Figure 4.3 Visual Designer program flowchart



Figure 4.4 Matlab program flowchart

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4.2.1 Visual Designer program

The Visual Designer program (Fig. 4.5) was designed for data acquisition, processing and control. Constant block 5 (Fig. 4.5) will be referred as 5 block or 5; other blocks will be similarly referred throughout program discussion. For better understanding, the blocks are referenced with the relevant figures numbers inside the parenthesis. It is recommended for better understanding of the Visual Diagram programs to study the function of each block as outlined in Appendix D. Control voltage (0-8.25 volts) and motor frequency (corresponding) terms are used as synonyms in the program discussion. The logical blocks represented with signs in the program are double quoted e.g. "==""" to avoid confusion in the program discussion.

The constant block 5 provides an initial control voltage of 5 volts through FB1 and RampOutput blocks (Fig. 4.5) to the motor drive. SB block (Fig. 4.6) of the Ramp Output block contains encoding for smooth acceleration/deacceleration of motor speed. Details of the SB block are shown in Fig. 4.7. If Reqd Speed (required speed) is greater than Prev Speed (previous speed), then ">" block (Fig. 4.6) sends a high (True) signal else the ">" block sends a low (False) signal to the SB block. The SB block has identical logic and blocks for the high and the low signal from the ">" block, expect until the execution of Do...While 1 block (Figs. 4.8 and 4.9).

Further, if the *Reqd Speed* (required speed) and the *Prev Speed* (previous speed) are equal, then "==" block (Fig. 4.7) sends a high (True) signal, else the "==" block sends a low (false) signal to *If else* block (Fig. 4.7). If the signal is high, then the *Reqd Speed* input (4.8 (a)) is directly sent to *Output* block (Fig. 4.6), through *Reqd speed* output (Fig. 4.8) else *Do..While 1* block (Fig. 4.8 (b)) is executed and then, the required speed is sent to *Output* block (Fig. 4.6)

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through the *Reqd speed* output. Further, if the required speed is greater than the previous speed, then the *Do..while 1* loop (Fig. 4.9 (a)) is executed, else the *Do..while 1* loop (Fig. 4.9 (b)) is executed. For every do loop, the x+P0 or x-P0 blocks (previous speed) is updated by constant *P0* until the *Reqd Speed* input (Fig. 4.9) is equal to the output from the x+P0 or x-P0 blocks. "x" represents the previous speed. If the required speed is greater than the output from the x+P0 block (Fig. 4.9 (a)) then do loop continues, else do loop is terminated. If the output from the x-P0 block is greater than the required speed (Fig. 4.9 (b)) then do loop continues, else do loop is terminated.



Figure 4.5 Main Visual Designer program

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Figure 4.6 Detail connections of Ramp Output block (Fig. 4.5)



Figure 4.7 Details of SB block for the low and the high signal (Fig. 4.6)

After the do-loop is terminated and if the pervious speed is not equal to the required speed, then "~=" block (Fig. 4.6) sends a high signal, else the "~=" block sends a low signal to $Data_Acq$ block (Fig. 4.5) through Mos_Chang output (Fig. 4.6). If the signal is high, then Avg_acc block (Fig. 4.10 (a)) is executed and output from the Avg_acc block (Fig. 4.10 (a)) is sent to Amp block (Fig. 4.5) else averaged acceleration is directly sent to the Amp block through Avg_acc output (Fig. 4.10).



(b) False case

Figure 4.8 Details of *If else* block (Fig. 4.7); (a) high signal (b) low signal ("==") In this paragraph, all the blocks belong to Fig. 4.11. The *Avg_acc* block is designed to average the acquired one channel signal. *Input Ch1* block performs the hardware input data acquisition. The data acquired is multiplied with calibration constant and then, *Window* block is used to modify the parameters of *Cut 1* block in order to obtain satisfactory signal outputs. *FFT 1* block implements the Fast Fourier Transform technique that converts the acquired time base signal to frequency domain signal. *Max* block stores maximum value obtained from the frequency domain signal in its single element buffer. This maximum value is proportional to maximum acceleration, i.e. $\omega^2 A$, for each frame of data acquisition. *Mov_avg* block averages the maximum value obtained from each frame and then, sends the averaged value to the *Amp* block through the *avg_acc* output.

Calc Fre block (Fig. 4.6) maps the control voltage to the motor frequency (Hz). The frequency is sent to Div zero block (Fig. 4.5) through Cut 1 and ==0 blocks. The ==0 and the

Div zero blocks check that if the frequency is zero, then send a numeric value of 1, else multiplies the frequency with 2π and then, square and send the output to the Amp block.



(b) Decreasing speed



for (a) Increasing speed (b) Decreasing speed

In this paragraph, all the blocks belong to Fig. 4.5. *M* block stores and sends maximum amplitude to *Ampdiff* block. The *Ampdiff* block subtracts the maximum amplitude from the output from the *Amp* block and then, sends the result to *pack* block. *Voltdiff* block calculates corresponding voltage difference and then, sends the result to the *pack* block. The packed data is sent to Excel worksheet through *num* and *Data_excel* (Dynamic Data exchange) blocks. The other blocks are used for proper functioning of the program.



(a) True case

Avg_acc Avg_acc

(b) False case





Figure 4.11 Details of Avg_acc block (Figure 4.10 (a))

4.2.2 Matlab program

Matlab program (Appendix E) continuously reads the amplitude and voltage difference from the Excel worksheet. The amplitude difference is normalized with the current maximum amplitude. The normalized amplitude difference and corresponding voltage differences inputs are fuzzified and then, the fuzzy inference engine determines which output rules are on according to the fuzzified inputs. The output rules are defuzzified and stored in Chang_volt variable (List E.1). The heuristic rules are used for stability and to mimic operator's knowledge as explained in Section 3.8.

Chang_volt block of the Visual Designer program (Fig. 4.12) is continuously reading the Chang_volt variable from the workspace of the Matlab program. *Reqd speed* block (Fig. E.8) adds the output from the *Chang_volt* block, and the maximum voltage corresponding to the maximum amplitude and then, sends the result to the *Reqd Speed* block (Fig. 4.6). Thus repeating the Visual Designer and Matlab programs until the Chang_volt variable is within the range of -0.006 and 0.006.



Figure 4.12 Details connection of *Check for voltage* block (Figure E.2)

4.3 Experimental Results and Discussions

The overall system response shown in Fig. 4.13 was studied before running the experiments. The experiments were performed to establish repeatability and efficiency of the

fuzzy control method for a dynamical system having constant stiffness, variable mass and variable damping coefficient. Three experimental setups were used to establish the reliability and effectiveness of the control method and to study the effect of system mass change and the effect of wet grains.

The experimental data is written in ASCII format to a file using the Visual Designer program. The ASCII file can be read through a tab limited Excel format. The ASCII file was then opened through an Excel worksheet. All response curves were plotted using the Excel worksheet.



Figure 4.13 System frequency response curve

The results for the empty bed are shown in Table 4.2 and the response curves are shown in Figs. 4.14 to 4.17, 4.26 and 4.27.

	Empty bed			
Response No.	1	2	3	
ω _{nf}	17.07	17.07	17.07	
$\omega_{_{op}}$	17.26	17.10	17.06	
$\frac{(\omega_{op}-\omega_{nf})}{\omega_{nf}}100$	1.11	0.18	-0.06	

Table 4.2 Empty Bed Variations

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In Table 4.2, ω_{nf} (new) is the system natural frequency in Hz; ω_{op} is the motor operating



frequency in Hz.





Figure 4.15 Empty bed frequency response 1



Figure 4.16 Empty bed amplitude response 2



Figure 4.17 Empty bed frequency response 2

The frequency variation was found to be within $\pm 2\%$ of the empty bed natural frequency 17.07 Hz, as shown in Figs. 4.15, 4.17 and 4.27. This establishes that the controller is effective and reliable. Also, the system acceleration is well above 1g, as required for fluidization of grains.

The second set of experiments was used to establish how the controller behaves when the system mass changes. The resonant frequency of the system should be between the two

extreme frequencies associated with an empty bed and a fully loaded bed. For a fully loaded bed, there exists no room for fluidization. The grains behave like a constant mass. The fuzzy control was able to keep the variation of operating frequency within a range of $\pm 4\%$. System mass was increased from 0 to 1 kg with a step size of 0.5 kg. System mass was decreased from 1 to 0 kg with a step size of 0.5 kg. The results for these experiments are shown in Figs. 4.18 to 4.21. Due to fluidization, the operating frequency of a loaded system is almost the same as for an empty bed. This phenomenon is more dominant for black eye grains than for chick pea grains. Fluidization was visually confirmed.



Figure 4.18 Bed loaded with 1kg of dry black eye grains



Figure 4.19 Bed loaded with 1 kg of dry black eye grains



Figure 4.20 Bed loaded with 0.5 kg of dry black eye grains



Figure 4.21 Bed loaded with 0.5 kg of dry black eye grains

Decrements of masses were used for chick pea grains. This set of experiments was done to study the effect of different grain types on system behavior. Results are shown in Figs. 4.22 to 4.25.



Figure 4.22 Bed loaded with 1 kg of dry chickpeas grains

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Figure 4.23 Bed loaded with 1kg of dry chickpeas grains



Figure 4.24 Bed loaded with 0.5 kg of dry chickpeas grains

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Figure 4.25 Bed loaded with 0.5 kg of dry chickpeas grains

	Black eye grains		Chick peas grains	
Mass	1kg	0.5 kg	1 kg	0.5 kg
ω_{nf}	16.531	16.795	16.531	16.795
ω _{op}	17.100	17.101	16.764	16.855
$\frac{\left(\omega_{op}-\omega_{nf}\right)}{\omega_{nf}}100$	3.442	1.82	1.40	0.35

Table 4.3 Summary of Decrement Results for Both Grain Types

Blackeye grains were fluidized at lower acceleration as compared to chickpeas grains. The minimum frequency required for fluidization of black eye grains is lower than that for chick pea grains.

The study of mass increment for black eye grains was conducted for establishing the robustness of the controller. Initially, the system was empty; and then two increments, each of 0.5 kg, were used to load the system. The system response is given in Figs. 4.26 to 4.31.









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Figure 4.28 Bed loaded with 0.5 kg of blackeye grain



Figure 4.29 Bed loaded with 0.5 kg of blackeye grain



Figure 4.30 Bed loaded with 1 kg of blackeye grain mass



Figure 4.31 Bed loaded with 1 kg of blackeye grain mass

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	Black eye grains		
Mass	ss 0 kg 0.5		1 kg
\mathcal{W}_{nf}	17.07	16.795	16.532
- W _{op}	17.06	17.062	17.00
$\frac{(\omega_{op}-\omega_{nf})}{\omega_{nf}}100$	0.05	1.59	2.83

Table 4.4 Summary of Increment Results

The third setup contained dry grains and damped grains. Equal masses of dry and damped grains were used. The objective was to study the effect of damping on fluidization and amplitude response. The fluidization was visually confirmed. The fluidization occurred at a peak acceleration of 4 g's for the wet grains and 2 g's for the dry grains. The response curves are shown in Figs. 4.32 to 4.35.



Figure 4.32 Bed loaded with 1.12 kg of dry black eye grains

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Table 4.5 State of Wet Grains

Weight of dry grains	0.5Kg
Weight of wetted grains	1.12kg
Started at	May 10@ 1.00pm
Ended at	May 12@ 12.02pm



Figure 4.34 Bed loaded with 1.12 kg of wet black eye grains



Figure 4.35 Bed loaded with 1.12 kg of wet black eye grains

	Black eye grains	
Condition	Wet	Dry
ω_{nf}	16.470	16.470
ω _{op}	16.949	16.956
$\frac{(\omega_{op}-\omega_{nf})}{\omega_{nf}}100$	2.91	2.95
Peak displacement mm	4.29	4.72

Table 4.6 Summary of Wet and Dry Results

Table 4.6 shows that the system loaded with the same mass (1.12 kg) of dry or wet grains has almost identical resonant frequency. This was expected because, for a low damping coefficient, there is very little change in resonant frequency. The system vibration amplitude is lower for wet grains (4.29 mm) compared to dry grains (4.72 mm).

The controller was tested for various conditions. It can be concluded that the controller has preformed its functions effectively.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

A fuzzy logic controller is developed and implemented for a resonant vibration dryer. With the controller, the grain drier may operate automatically at the resonant condition to achieve the best possible drying efficiency. Various experiments were performed for the drying system loaded with different amounts of grains and different types of grains including the empty-load situation. The system response curves showed that the controller is effective for all situations. During the experiments, grain fluidization was achieved and verified visually under the designed resonant condition.

The Lagrange equations were used to establish equations of motion of an empty system having three degrees of freedom. The results from the three degrees-of-freedom analysis were used for the placement of an accelerometer.

5.2 Future work

A mathematical model may be developed for the effective force transferred to grains and the minimum amplitude requirement for fluidization. A moisture sensor may be brought into the control system for the purpose of monitoring and terminating the drying processes. The digital signal acquired may be filtered before transforming to the frequency domain. To achieve pure translational motion, guide rails may be replaced with vertical slides and other mechanisms. The controller can be developed further for multiple degrees of freedom.

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APPENDIX A

SYSTEM ANALYSIS AND MODIFICATION

A.1 Visual Designer Program

This section gives programming details. Reader can directly go to section A.2.



Figure A.1 Visual Designer program for frequency response

The program, Fig. A.1, was designed for analyzing the frequency response of the system. The rules for representing the Visual Designer block, section 4.2.1, are valid for this discussion. Constant block 3.8 (Fig. A.1) provides an initial voltage of 3.8 Volts through *FB1* (Fig. A.1)

and *Ramp Output* blocks (Fig. A.2) to motor drive. *SB* block (Fig. A.2) is designed for smooth acceleration and deceleration of motor speed. Details are given in section 4.2.1. The output value of the *FB1* block is wired to *Max_volts* input (Fig. A.2.) The *Max_volts* input is wired to *Max_volts* input (Fig. A.3) of *Check for voltage* block (Fig A.3). The *Check for voltage* block is designed for providing initial voltage of 3.8 Volt and then, update and send new voltages, in incremental steps of 0.1 Volts (parameter set in *Chang_volt* block) until 8.25 Volts, to motor drive. For every updated voltage (new motor speed), *Data_Acq* block (Fig. A.1) starts acquiring data, details are given earlier in section 4.2.1; and the system states are written in ASCII format to a file through *Filew* block (Fig A.1). The ASCII file can be read through tab limited Excel format. The ASCII file was then opened through an Excel worksheet. All response curves were plotted using the Excel worksheet. Other blocks are used for proper functioning of the program.



Figure A.2 Ramp Output block



Figure A.3 *Check for voltage* block

A.2 Machine modification

The original system response is shown in Figs. A.4 to A.6. The acceleration becomes stagnant beyond 22 Hz, Fig. A.4. The motor did not accelerate, even as a higher control voltage (0-8.25 volts) is being sent to the motor drive, beyond 22 Hz.

The motor was calibrated without vibration, Fig. A.6 and was able to achieve 1800 rpm or 30 Hz. The system was designed so that the motor vibrates with the vibratory dryer. The motor withdraws 90 Volts and 0.5 Amperes from the motor drive when vibrating at 22 Hz. This drives the motor drive into the saturation state.

The motor is rated for 90 Volts and 0.5 Ampere. The control drive parameters were set so that it goes into saturation at 90 Volts and 0.7 Amperes. The motor and its drive were disassembled from the system. The motor was stalled in a vice. An ammeter was connected in series with the motor drive, and the 0.5 Ampere rating fuse was replaced with a 3/4 Ampere rating fuse. After switching the motor drive on, the current regulation trim pot was adjusted



Figure A.4 Original system response (Acceleration / Time)



Figure A.5 Original system response (Amplitude / Time)



Figure A.6 Calibration of motor (Frequency / Drive Voltage)

so that the ammeter reads 0.7 Ampere (the motor stalled) when the motor drive just goes into saturation (Red bulb light up on circuit board of the control drive). The motor was reassembled and tested but still the motor drive goes into the saturation state.

There was not much load on the motor, i.e., two phenolic gears and two eccentric masses of 160 grams/each. Friction between guide rails and sliders is small. After reviewing several designs, it was decided to alter the mechanical behavior of the system. For fluidization, effective acceleration greater than 1 g is required. As system acceleration is greater than 10 g's, mass can be added to reduce the natural frequency so that the motor drive does not into saturation and the acceleration is still greater than 1 g. Equation A.1 is used for calculating the required additional mass. An additional mass of 8.625 kg is needed to reduce the system natural frequency to 17 Hz. There were several options available to place this weight e.g., replacing pegboard with mild steel (M.S.) sheet, assembling M.S. flats on an outer boundary of Lucite container etc. After reviewing several designs, two M.S. flats (75 mm wide, 25 mm thick and 275 mm long) were drilled and assembled to the side of the Lucite wall container. A

net mass of 8.5 kg is added to system. The added mass reduced the natural frequency to 17.07 Hz.

$$f_n = \frac{1}{2\pi} \left(\sqrt{\frac{K}{(M_R + M_{\mu})}} \right)$$
(A.1)

where, K is the Total Stiffness (173098.5 N/m) [1]; M_{le} is the original empty system mass, (6.562 Kg); f_n is the new natural frequency; M_R is the required additional mass.

The modified system response is shown in Fig. A.7 and Fig. A.8. The maximum acceleration and displacement amplitude of the system decreased but they are sufficient for the fluidization of grains.



Figure A.7 System response after adding mass (Acceleration/Frequency ratio)



Figure A.8 System response after adding mass (Amplitude/ Frequency ratio)

APPENDIX B

PHYSICAL PROPERTIES

B.1 Center of Gravity

B.1.1 Practical Method

If an object is attached to a flexible string whose other end is pivoted to a frame, and allowed to move in a gravitational field, equilibrium will occur in such a way that the center of gravity becomes collinear with the string direction. This fundamental characteristic is used to determine the center of gravity. The drying machine was dissembled from the base plate and attached to one end of a thin flexible steel wire. The other end of steel wire was pivoted to a steel frame. At equilibrium, the steel wire was projected on the surface of machine such that it gives two points. Ideally, if these two points are connected and extended, it should be collinear with the steel wire. Only one more set of points were sufficient to establish the C.G. Similarly machine was attached at two different points and projected points on the machine were marked. Short aluminum channels of the machine were attached to the steel wire. The next step was to establish frame of reference to locate dimensions of the points. Lower right front corner (looking at front of motor) of short aluminum channel was used as the origin and distances of all points from the origin were measured. The directions of axes considered are X - Axis is formed by the right hand coordinate system; Y - Axis is parallel to the motor axis and positive in the direction as we move from front to back of the motor; Z - Axis is considered in the vertical direction and positive in the upward direction.

A 3D CAD model of the aluminum channel was created. The corresponding points (3 pairs) were located and joined by the three dimensional lines. The mean of the measured distances between different points were taken and averaged. As the experimental result was not accurate an analytical method was used to verify the results, details are given in section B.1.2. The results were within a range of 5 % error compared to the analytical method.

Points	X mm (inches)	Y mm (inches)	Z mm (inches)
1(a)	0.00	14.17 (0.558)	19.96 (0.786)
1(b)	314.33 (12.375)	24.33 (0.958)	97.41 (3.835)
2(a)	0.00	14.96 (0.589)	127.89 (5.035)
2(b)	314.33 (12.375)	15.11 (0.595)	13.06 (0.514)
3(a)	0.00	17.12 (0.674)	68.2 (2.685)
3(b)	314.33 (12.375)	15.11 (0.595)	53.98 (2.125)

Table B.1 Coordinates of Projected Points

The dimensions of all the data points in z axis and three dimensions lines are shown in Fig. B.1.



Figure B.1 Side view of aluminum channel for further operation

B.1.2 Analytical Method

Analytical method requires the distribution of various masses and their distances in a defined coordinate system. Major subcomponents were dissembled; their masses were measured and recorded in Table B.2.

S.No.	Description of item	Quantity	Mass (g)
1	Lucite container and	1	3822
2	Rear Aluminum Channel	1	370
3	Front Aluminum Channel	1	380
4	Motor	1	1332
5	Gear assembly/each	2	198/each
6	Bearing housing	1	116
7	Springs (lower and upper	4	187/pair
8	Sliders	4	250/each
9	M.S flat	2	4250/each

 Table B.2 Weights of different Components of Machine

The chosen reference planes for measurements are Lucite side wall plane parallel to motor axis for measuring x- distances; Lucite side wall plane parallel to motor axis for measuring ydistances; Lucite container top plane parallel to motor axis for measuring z-distances. These planes are shown in Figure B.2. The distances of center of gravity of each part was determined from these planes and are used for determining center of gravity of machine.

S.No.	Name of part	Mass(kg)	Distance(mm)	Product
1	Lucite and pegboard	3.822	196.85	752.36
2	Gear and eccentric weight	0.4	184.15	73.66
3	Front Aluminum channel	0.38	234.95	89.28
4	Bearing housing	0.258	222.25	57.34
5	Motor	1.332	281.31	374.70
6	Back Aluminum channel	0.37	350.52	129.69
7	M.S flat	8.5	203.2	1727.20
	Total of Column	15.062		3204.23
	Distance from reference plane		$Y_{mean} = 3204.23/15.062$	
			<u> </u>	= 212.74

Table B.3 Centre of Gravity Calculation, Y - axis

 Table B.4 Centre of Gravity Calculation, X - axis

S.No.	Name of part	Mass(kg)	Distance(mm)	Product
1	Lucite and pegboard	3.822	153.99	588.54
2	Driver gear	0.2	158.75	31.75
3	Driven Gear and eccentric weight	0.2	95.25	19.05
4	Front Aluminum channel	0.38	153.99	58.50
5	Bearing housing	0.258	95.25	24.57
6	Motor	1.332	158.75	211.46
7	Back Aluminum channel	0.37	153.99	56.97
8	M.S. flat	4.25	-012.7	-53.98
9	M.S. flat	4.25	323.85	1376.36
	Total of Column	15.062		2313.22
	Distance from reference plane		$X_{mean} = 2313.$	22/15.062
				= 153.58

Table B.5 Centre of Gravity Calculation, Z - axis

S.No.	Name of part	Mass(kg)	Distance(mm)	Product
1	Lucite Container	0.018	200.03	3.60
2	Peg Board	3.804	400.05	1521.79
3	Short Aluminum channel	0.602	476.25	286.70
4	Motor+gears+ Bearing housing	1.988	495.30	984.66
- 5	Long Aluminum channel	0.15	520.7	78.11
6	M.S. flat	8.5	381	3238.5
	Total of Column	6.42		6113.36
	Distance from top surface		$Z_{mean} = 6113.36/15.062$	
				= 405.88



Figure B.2 Center of gravity position

B.2 Mass moment of inertia

Mass moments of inertia depend not only on mass distribution, but also on location of the rotational axes. An experimental method was used to calculate the mass moments of inertia.

Simple pendulum equation and parallel axis theorem are used to determine the system mass moment of inertia. The equation of motion for simple pendulum is:

С m_{b}

Figure B.3 Simple pendulum

 $I\ddot{\theta} + m_b g R \theta = 0$

where, *I* is the rotational inertia about pivot (attached holes of iron bars); θ is the angle of pendulum; *R* is the length of rod (distance of pivot from C.G. of system); m_b is the mass of pendulum (System mass); *g* is the gravitational acceleration. The natural frequency (f_n in Hz and ω_n in rad/s) of the system shown in Fig. B.3 is:

$$\omega_n = 2\pi f_n = \sqrt{\frac{m_b g R}{I}}$$
(B.2)

If f_n , m_b , g and R are known, the moment of inertia about the axis O can be determined from Eqn. B.2.

The moment of inertia of any object about an axis through its center of mass is the minimum moment of inertia for an axis in that direction in space. The moment of inertia about any axis parallel to that axis through the center of mass is given by

$$I_{parallelaxis} = I_{CG} + m_s d^2 \tag{B.3}$$



Figure B.4 Parallel axis theorem

where, I_{CG} is Center mass moment of inertia; m_s is system mass (M_{t}) ; d is the distance between two parallel axis, $I_{parallelaxis}$ is an axis parallel to the axis passing through C.G.

B.2.1 Experimental setup

Two mild steel flat (30 mm \times 6 mm, 710 mm lg.) were used for experimental setup. After drilling 7mm holes, flat were screwed together at the drilled holes. After securing the holes, the other end was bent at 90°. The plates were clamped to a member of the frame as shown in Figs. B.5 and B.6.

The original bolts (located at the same height and at opposite end to each other) of the machine were replaced with long bolts. These long bolts were assembled to the corresponding holes in the flat. Final adjustments were made, so that machine sits properly. The free undamped vibration theory and parallel axis of theorem were used to calculate the moment of inertia about the C.G. of the system.

The experimental setup used for finding moment of inertia is shown below:



Figure B.5 Experimental setup for finding I_{vv}



Figure B.6 Experimental setup for finding I_{xx}

The fundamental natural frequency of the system was measured experimentally. An accelerometer was mounted at the farthest point (near the top edge of the Lucite wall) on the system and in the direction of the motion. The system was given a small initial displacement. Fig. B.7 shows the time domain and its frequency domain response of the signal.



Figure B.7 (a) Time domain response. (b) Frequency domain response.

B.2.2 Determining mass moment of inertia

The distance between pivot and center of gravity can be determined. Since system mass and natural frequency is known, the moment of inertia about pivot axis may be calculated from Eqn B.2. The moment of inertia about parallel axis passing through C.G. is calculated from Eqn. B.3. Due to redesigning of machine, the mass moment of inertia of individual M.S. flats are recalculated at previous C.G. and added to original system mass moment of inertia. Then, using parallel axis theorem, mass moment of inertia at new C.G. is calculated.



Figure B.8 Distances of pivot from previous center of gravity

Table B.6 Finding Moment of Inertia I_{xx}

A1	Fundamental free vibration frequency(X-axis)	0.656Hz
A2	Total mass of system	7.92kg
A3	Gravity	9.81m/s ²
A4	Pivot distance in y direction from C.G.	0.711e-3 m
A5	Pivot distance in z direction from C.G.	0 .053 m
A6	Radial distance	0.053m

$$\omega(A1) = \sqrt{A2 \cdot A3 \cdot A6/I_{pxx}}$$

$$I_{pxx} = 0.242kgm^{2}$$

$$I_{gxx} = I_{pxx} - (A2 \cdot A6^{2}) = 0.22kgm^{2}$$
(B.4)

Description	Mass	M.I. neutral	$\Delta z(m)$	$\Delta y(m)$	M.I.	@
	(kg)	axis xx (kgm ²)			P.C.	G. (kgm ²)
M.S. flat 1	3.83	0.0021	0.056	0.022		0.0174
M.S. flat 2	3.83	0.0021	0.056	0.022		0.0174
Machine	6.562	0.22	0	0		0.22
Total mome	ent of inerti	a xx @ previous C	.G.			0.2548
	Total system mass			15.06	52 kg	
ΔZ (minus)			0.0)31m		
Γ	ΔΥ			0.0)13m	
	Total moment of inertia xx@ new C.G.			0.238 k	g.m ²	

Table B.7 Finding Moment of Inertia I_{xx} at New C.G.

where, Δy is the distance between mass center of flat and previous C.G. in y-axis; ΔY is the distance between new C.G. and previous C.G. in y-axis; Δz is the distance between mass center of flat and previous C.G. in z-axis; ΔZ is the distance between new C.G. and previous C.G. in z-axis; Total moment of inertia xx @ previous C.G. is equal to the sum of M.I. @ P.C.G. of original machine (xx) and (M.I around neutral axis of flats + 4.25 ($\Delta z^2 + \Delta y^2$)); Total moment of inertia xx @ new C.G. is equal to the subtraction of 15.062($\Delta Z^2 + \Delta Y^2$) from the Total moment of inertia xx @ previous C.G.

Table B.8 Finding Moment of Inertia I_{yy}

B1	Fundamental free vibration frequency(X-axis)	1.01Hz
B2	Total mass of system	7.92kg
B3	Gravity	9.81m/s ²
B4	Pivot distance in x direction from C.G.	0.140 m
B5	Pivot distance in z direction from C.G.	0 .0533 m
B6	Radial distance	0.15m

$$\omega(B1) = \sqrt{B2 \cdot B3 \cdot B6 / I_{pyy}}$$

$$I_{pyy} = 0.288 kgm^{2}$$

$$I_{gyy} = I_{pyy} - (B2 \cdot B6^{2}) = 0.11 kgm^{2}$$

(B.5)

Description	M.I. Neutral	Δz (m)	Δx (m)	M.I. @	P.C.G.
	axis yy (kgm ²)			(kgm ²))
M.S. flat 1	0.0021	0.056	0.165		0.1311
M.S. flat 2	0.0021	0.056	0.168		0.1354
Machine	0.11	0	0		0.11
Total mome	ent of inertia yy @ p	revious C.G.		0.3765	
To	otal system mass		15.	15.062 kg	
Δ	ΔZ (minus) 0.031m				
	ΔΧ			0.012m	
Total moment of inertia yy@ new C.G.			G. 0.363	3 kg.m ²	

Table B.9	Finding	Moment	of	Inertia I	at New	C.G.

where, Δx is the distance between mass center of flat and previous C.G. in x-axis; ΔX is the distance between new C.G. and previous C.G. in x-axis; Total moment of inertia yy @ previous C.G. is equal to the sum of M.I. @ P.C.G. of original machine (yy) and (M.I around neutral axis of flats + 4.25 ($\Delta z^2 + \Delta x^2$)); Total moment of inertia yy @ new C.G. is equal to subtraction of 15.062($\Delta Z^2 + \Delta Y^2$) from the Total moment of inertia xx @ previous C.G.

APPENDIX C

VIBRATION ANALYSIS

C.1 Three Degree of Freedom Undamped Vibration Analysis

The C.G. of the machine is chosen as the origin of the coordinate system. The axis directions are chosen as given in section B.1.1.

The Lagrange equations were used to formulate the basic vibration equations. The equations were then solved using the modal analysis. Three dimensions considered are shown below:





Figure C.1 Degrees of freedom for Lagrange analysis

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The kinetic energy of the system is,

$$T = M_{t} \dot{z}^{2} / 2 + I_{x} \dot{\theta}_{1}^{2} / 2 + I_{yy} \dot{\theta}_{2}^{2} / 2$$
 (C.1)

where at any instant time (t), M_1 is total system mass; \dot{z} is the velocity in vertical directions; I_{xx} is mass moment of inertia around X-axis; I_{yy} is mass moment of inertia around Y-axis; $\dot{\theta}_1$ is the angular velocity of bed, measured in YZ plane; $\dot{\theta}_2$ is the angular velocity of bed, measured in XZ plane.

The potential energy stored in the guide rails and other members is neglected and only energy stored in the springs is considered. It is assumed that springs have linear coefficient of elasticity for the range of displacement considered. The potential energy of system,

$$\mathbf{U} = \left[(z + l_1\theta_1 - l_4\theta_2)^2 + (z + l_1\theta_1 + l_3\theta_2)^2 + (z - l_2\theta_1 + l_3\theta_2)^2 + (z - l_2\theta_1 - l_4\theta_2)^2 \right] k/2$$
(C.2)

where at any instant time (t), z is the dynamic vertical displacement measured from static equilibrium, in Z – axis; θ_1 is the dynamic angular displacement of bed measured from static equilibrium, in YZ plane; θ_2 is the dynamic angular displacement of bed measured from static equilibrium, in XZ plane; l_1 is the distance between C.G. and front guide rail measured in YZ plane; l_2 is the distance between C.G. and back guide rail measured in YZ plane; l_3 is the distance between C.G. and left guide rail measured in XZ plane; l_4 is the distance between C.G. and right guide rail measured in XZ plane; K is the stiffness of the helical springs.

The Lagrangian is L = T-U. The Lagrange equation for undamped free vibration:

$$\frac{\partial(\partial L}{\partial \dot{q}_i})}{\partial t} - \frac{\partial L}{\partial q_i} = 0 \tag{C.3}$$

where $q_i = z, \theta_1, \theta_2$ for i=1, 2, 3. Let $\{q\}$

$$\{q\} = \begin{cases} z \\ \theta_1 \\ \theta_2 \end{cases}$$

Free undamped vibration equations are given below:

$$[M]{\ddot{q}} + [K]{q} = \{0\}$$
(C.5)

where the mass matrix [M] and stiffness matrix [K] are

$$\begin{bmatrix} M \end{bmatrix} = \begin{bmatrix} M_{t} & 0 & 0 \\ 0 & I_{xx} & 0 \\ 0 & 0 & I_{yy} \end{bmatrix} = \begin{bmatrix} 15.062 & 0 & 0 \\ 0 & .238 & 0 \\ 0 & 0 & .363 \end{bmatrix}$$
(C.6)

$$\begin{bmatrix} K \end{bmatrix} = \begin{bmatrix} 4 & 2(l_1 - l_2) & 2(l_3 - l_4) \\ 2(l_1 - l_2) & 2(l_1^2 + l_2^2) & (l_1 - l_2)(l_3 - l_4) \\ 2(l_3 - l_4) & (l_1 - l_2)(l_3 - l_4) & 2(l_3^2 + l_4^2) \end{bmatrix} k = \begin{bmatrix} 1730985 & -190408 & 0 \\ -190408 & 484676 & 0 \\ 0 & 0 & 5106406 \end{bmatrix}$$
(C.7)

The natural frequencies of the three degree of freedom system may be determined from

$$\det[K] - [M]\omega^2| = 0 \tag{C.8}$$

The roots of the Eqn. C.8 are the natural frequencies of the system. The natural frequencies are given below:

 $\omega_{n1} = 106.56 \text{ rad/s}$ $\omega_{n2} = 116.38 \text{ rad/s}$ $\omega_{n3} = 133.90 \text{ rad/s}$

The normalized modal matrix is

$$[P] = \begin{bmatrix} -0.255 & 0 & 0.037 \\ -0.277 & 0 & -1.8974 \\ 0 & 1 & 0 \end{bmatrix}$$

(C.9)

(C.4)

APPENDIX D

VISUAL DIAGRAM BLOCKS

Block	Function
	This block reads analog input data from the specified intelligent
	Instrumentation DASport, unit using high-speed analog input
Input Ch1	techniques.
	This block writes analog output data from the specified intelligent
A # \$ \$	Instrumentation DASport, unit using high-speed analog input
Output	techniques.
5	This block performs a logical OR functions; it accepts two to eight
22	inputs and has single output.
Or	
	This block performs a logical AND functions; it accepts two to eight
	inputs and has single output.
And	
	Sets the output buffer values t TRUE or FALSE based on the trigger
	conditions.
Threshold	
	A block which allows one of several actions to be performed based
	on the value presented to the Selection control input. It performs the
II eise	II-Eise functions, when input is either i rue of Paise.
	A block which contains other blocks and, because of its ability to be
Subaram	reduced to a single icon.
Subyram	Input to a subgram. Can be used in the subgram as a source of data
Subaram input	for other blocks
	Output from a subgram Connect to a block of this type to output
Subaram output	data from a subgram
	A subgram which executes its contents repeatedly until a condition
	is false
Dowhile	
Loop Com	The output of this block indicates the number of Dowhile loops
Loop Count	executed.
Continent	The block whose input value determines whether the parent
Continue?	Dowhile loop block loops again.
	Single or multi-line edit box that in which you can enter a string and
	pass it to the output buffer.
Alphanumeric input	
	Fills the output buffer with constant data.
	Edit has where a number can be directly entered
4.56	Eur box where a number can be directly entered.
Numeric edit	
Tunnone out	1

1

	Performs a DDE Poke transaction with the specified server
	r onorms a <i>BBB</i> r oko transaction with the spectrue set of.
DDE server	
	Receives and outputs data from other Windows applications via
	DDE services
DDE client	
FFT	Performs a Fast Fourier Transform on a single input huffer
	r onomis a rast rounor transform on a single mpat outfor.
EFT 1	
MAX	Finds the maximum value and the index of the value in the input
hat	buffer
Max	
	This function block performs a moving average operation on the
	input data. It accepts one required input and one optional input and
Moy ava	has a single output
	Calculates a user defined equation
f(x)=	Calculates a user defined equation.
Fruation	
	Divides two to eight inputs and outputs this quotient
Х/У	Divides two to eight inputs and outputs this quotient.
Division	
YaY	Adds two to eights inputs and outputs this sum.
Add	
x-v	Subtracts two to eights inputs and outputs this difference.
Subtraction	
xy	Multiplies two to eight inputs and outputs this product.
Multiply	
	This block is used to generate timing information for low-speed data
Timor	acquisition and control application.
	This block is used to combine two or more data buffers into a single
	multi-channel buffer
Pack	
	This block obtains a subset of a data buffer by copying N data points
	from its input to its output starting at the specified OFFSET.
Cut	
<num></num>	Formats output string with input buffer values according to
etaoin	template.
String Format	
1.41	Displays the first point of a numeric input buffer.
Digital Motor	
	Accents two inputs on initial value input and a feedback input. The
	first time the block executes, the output is equal to the initial value
	input Thereafter the output is equal to the feed hear input
Feedback	mput. Thereafter, the output is equal to the feed back input.



APPENDIX E

MATLAB PROGRAM

List E.1. Matlab program

```
FH=ddeinit('excel', 'Amplitude.xls');
con=1;
amp_chan=0;
volt_chan=0;
Chang_volt=-0.666;
TChang_volt=0;
prev_Chang_volt=0;
fismat=readfis('Ampfuzzy_april_3_norm_mod');
prev_voltmax=0;
final_var=5;
continuous=1;
t=clock;
```

while (continuous==1)

p_amp_chan=amp_chan; %previous settings
p_volt_chan=volt_chan;

%for first loop these values will be zero %for second loop these values will be non-zero

```
amp_chan=ddereq(FH, 'rlc1:rlc1');% read current settings
volt_chan=ddereq(FH, 'rlc2:rlc2');
elasptime=ddereq(FH, 'rlc3:rlc3');
ampmax=ddereq(FH, 'rlc4:rlc4');
```

if ampmax==0 % ampmax is used as divisor for normalization
 ampmax=1;

end

```
while volt_chan~=-1 & final_var==0
    % necessary for proper timings of programs
    % for second iteration after inactive status
    amp_chan=ddereq(FH, 'r1c1:r1c1');
    volt_chan=ddereq(FH, 'r1c2:r1c2');
    ampmax=ddereq(FH, 'r1c4:r1c4');
    final_var=0;
```

```
end
```

```
while (p_volt_chan==volt_chan) | (volt_chan==0)
% for proper timing of visualdesigner and matlab
```

amp_chan=ddereq(FH, 'r1c1:r1c1'); volt_chan=ddereq(FH, 'r1c2:r1c2');

```
ampmax=ddereg(FH, 'r1c4:r1c4');
      disp('p_volt_chan');% for debugging
      disp(p_volt_chan); % for debugging
      disp('amp_chan'); % for debugging
      disp(amp_chan); % for debugging
      disp('volt_chan'); % for debugging
      disp( volt_chan); % for debugging
 end
prev_Chang_volt=TChang_volt;
      if final_var==0
            final_var = 5; % greater than zero for continuous
            TChang_volt = -1.25; % here TChang is changed so
            % that the next if block becomes false and fuzzy
            % logic starts again
      end
if TChang_volt>=-0.006 & TChang_volt<=0.006 & elasptime>40
      TChang_volt=0;
      rinal_var=0; %this starts the wait block in visual designer
else
      amp_chan=amp_chan/ampmax;
      if amp_chan>0.8 % when new search starts the max amplitude
                      % is set to zero and this results in
                      % abnormal changes amp_chan.
            prev_Chang_volt=prev_Chang_volt/2;
            %reduced space search by half
            amp_chan=0.01;
      end
      input1=[amp_chan volt_chan]';
      TChang_volt=evalfis (input1, fismat);
      %inputs to the fuzzy logic
      disp('fuzzychang');
      disp(TChang_volt);
      t=clock;
end
      if abs (prev_Chang_volt) < abs (TChang_volt)& con~=1&
            TChang_volt~=0 & prev_Chang_volt~=0
            % Heuristic stability
          if
                      prev_Chang_volt>0
                      if TChang_volt>0
                      TChang_volt=prev_Chang_volt-0.01;
                      else
                      TChang_volt=-prev_Chang_volt+0.01;
                      end
          else if
                      TChang_volt>0
                      TChang_volt=-prev_Chang_volt-0.01;
```

else

end

TChang_volt=prev_Chang_volt+0.01;

end

end

Chang_volt=TChang_volt; % Chang_volt is read by the Visual Designer Program.

disp('clock time');% for debugging disp(t(6)); % for debugging disp('prev_Chang_volt'); % for debugging disp(prev_Chang_volt); % for debugging disp('Chang_volt'); % for debugging disp(Chang_volt); % for debugging

con=con+1;

end

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EDUCATION

 M. A. Sc. – Mechanical Engineering, Ryerson University, Toronto, Ontario, Canada GPA 4.07/4.33 Sept. 2001 - Sept. 2003

- Courses taken: ME8107 Al for Mechanical Engineers, ME8135- Intelligent fuzzy Control, ME8123 - Mechanical Vibration, ME8116 - Dynamics and Control, EN8911 - Computer Methods for Engineering Computations, ME8115 - Finite Element Method
- **B.Eng.** Mechanical Engineering, May 1991 to May 1995 Punjab Engineering College, Panjab University, Chandigarh, India

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PUBLICATION

• V. Sudera, G. Liu and S. D. Yu, "Fuzzy Control of a Resonant Vibration Dryer," accepted for presentation at the ASME International Mechanical Engineering Congress and Exhibition (Paper # IMECE-2003-41632), Nov 15-21, 2003, Washington, D.C.