

# THE IMPACT OF DYNAMIC SIMULATION AND EXPERIMENT WITHIN THE ENGINEERING AND TECHNOLOGY EDUCATION

Abul K. M. Azad<sup>1</sup> and Youakim Al-Kalaani<sup>1</sup>

**Abstract:** This paper illustrates the introduction of realistic simulations and experimental components as a teaching material to enhance the student learning process. Two technically demanding areas are discussed, namely building management systems and flexible robotic manipulators. The former is illustrated with reference to a building services application, which is emulated via a laboratory scale test-cell. The later case is the study of a prototype single link flexible robotic manipulator system in terms of its simulation and control.

## INTRODUCTION

It has always been desirable for a faculty to introduce computer simulated and/or experimental systems, along with standard classroom and laboratory teaching. This will help students to be exposed to the practical details, so that they can appreciate the system complexities as well as the application of fundamental theoretical concepts [1]-[5]. In this way, students can be familiarized with real-life systems, which help them to get "the bigger picture" for their discipline.

However, this can be difficult when the problems are of a scale and complexity that does not allow the students to easily interact with the real plant. Hence, alternatives need to be found. The alternatives are to: a) develop laboratory scale prototypes to highlight areas of importance, b) visits to industrial sites to experience the scale and magnitude of a full plant and set-up, and, c) use of computer modeling and simulation to study the problem. In addition to classroom teaching, these are all extremely valuable avenues to pursue when training new recruits for a company so that they can have some feeling of real situations.

In this paper, two of the above approaches, such as a) and b) are going to be presented for two engineering problems. The problems considered in this paper are building management systems and flexible robotic manipulators. The experience of using these techniques on engineering graduate students at two UK Universities (the University of Sheffield and University of Portsmouth) has shown that these simple

and realistic experimental rigs along with computer modeling and simulations allow students to be much more receptive towards solving the underlying theoretical problems.

## BUILDING MANAGEMENT SYSTEMS

The area of building management system address all the aspects of building services and how these services can be provided for the user in a cost effective, reliable, and user friendly manner. These services can be quite extensive and can include everything provided within a building; some services included on this list are environmental control systems, voice and data communications, fire and smoke management, lifts, lighting, public utilities, and security. A block diagram of such a system is shown in Figure 1. To simplify the analysis, we will only focus on the environmental control aspects, so that comfort for the users is optimized. In order to make this even more tractable, we can distill some of the key features and map them onto a simplified model that can be used to analyze the application. This process of simplifying the problem is shown in Figure 2. In this figure, the gains and losses are simplified and stated as net gains or losses.

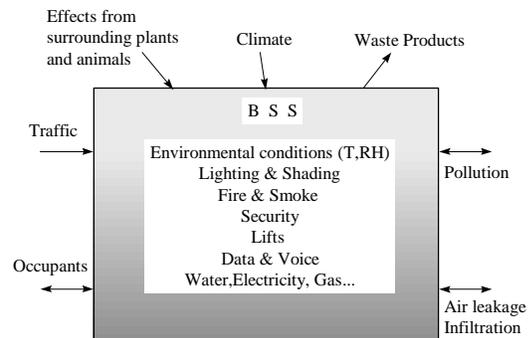


FIGURE 1  
BUILDING SERVICES SYSTEM.

Having obtained this rather simplified representation of the overall complex built environment problem, it is possible to consider how these influences can be included in a model that could be used for teaching and research. It is

<sup>1</sup> Department of Technology, Northern Illinois University, DeKalb, IL-60115, azad@ceet.niu.edu.

difficult to experiment on a full-scale building because of the long time constants and the complex stochastic effects present, which cannot be accurately measured [6]. A laboratory test-cell has therefore been developed as a platform to allow students to experiment with and gain better insight into the temperature control applications. Each side of the test cell has a heating element and a temperature sensor to form a temperature regulation loop. There are fans included on each side of the test cell to allow the simulation of ventilation effects. All the inputs and outputs of the system are connected to an interface card of a PC such that a computer control scheme can be implemented in a fairly straightforward manner.

It is clear that this simple test-cell contains all the vital ingredients of the temperature loop shown in Figure 2, but is much more flexible when it comes to experimentation for studying the effects of making particular changes. This test-cell is used to illustrate how an advanced model-based strategy can be developed and tested before it is implemented on a full scale Building Management Systems (BMS).

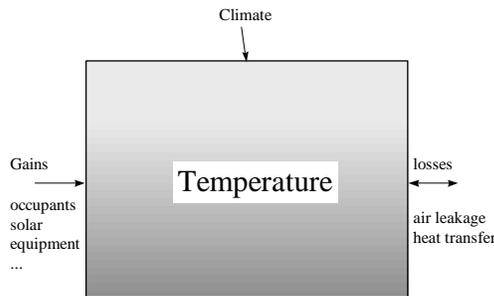


FIGURE. 2  
SIMPLIFICATION OF A BUILDING SERVICE SYSTEM.

**CASE-1: THE TEST CELL CASE STUDY**

The building management area is primarily concerned with the development of advanced model-based solutions to improve system performances and reduce energy consumption. Such solutions can be proactive when the decisions are based on model predictions. The idea is that if the models are good then much tighter control is possible thereby giving the occupants an improved environment to work in. The modeling techniques that can be explored include:

- a) models based on first principles (thermo-physical models);
- b) time series regression type models;
- c) steady state models;

- d) heuristic models based upon the concepts of soft computing, which use various combinations of neural networks, fuzzy logic, evolutionary algorithms, and probabilistic reasoning.

These models require data either to calculate or validate the model, and hence the test-cell offers students the ability to perform this modeling and/or modeling validation exercises. One such modeling technique is presented here.

**TIME SERIES MODELING**

The objective of the modeling exercise is to be able to predict the air temperature in each of the two zones ( $T_1$  and  $T_2$ ). In order to do this, those variables having an influence on the system needed to be identified and monitored: clearly, the heating input rates (Heater<sub>1</sub> and Heater<sub>2</sub> ( $W_1$  and  $W_2$ )), the disturbances due to the fans ( $F_1$  and  $F_2$ ) and the external air temperature  $T_{ext}$ . The effect of one heater on the air temperature in the neighboring cell might be best represented in the model by the temperature of the air in its own cell; the modeling process is aimed at establishing the most adequate inputs to be included and the best model configuration. Therefore, the temperature of the air inside each cell can be represented as a function of these variables in the following manner:

$$T_1(t) ? f_1(T_2(t), W_1(t), W_2(t), T_{ext}(t), e_1(t)) \quad (1)$$

$$T_2(t) ? f_2(T_1(t), W_1(t), W_2(t), T_{ext}(t), e_2(t)) \quad (2)$$

Equations (1) and (2) represent general, non-linear models, where  $f_1$ , and  $f_2$  stand for 'function of' the variables. The complexity associated with non-linear models is, in general, not desirable for practical purposes, and a linear modeling approach often suffices [7]. A linear difference operator format for, say, equation (1) with stochastic effects included can be written as:

$$A(z^{-1})T_1(t) ? z^{-k_1}B_1(z^{-1})W_1(t) ? z^{-k_2}B_2(z^{-1})W_2(t) ? z^{-k_3}B_3(z^{-1})T_{ext}(t) ? z^{-k_e}C(z^{-1})e_1(t) ? d \quad (3)$$

$$A(z^{-1})T_{right}(t) ? z^{-k_1}B_1(z^{-1})W_1(t) ? z^{-k_2}B_2(z^{-1})W_2(t) ? z^{-k_3}B_3(z^{-1})T_{ext}(t) ? z^{-k_e}C(z^{-1})e_1(t) ? d$$

where:

$$\begin{aligned} A(z^{-1}) & ? 1 + a_1z^{-1} + a_2z^{-2} + \dots + a_nz^{-n} \\ B_i(z^{-1}) & ? b_{i0} + b_{i1}z^{-1} + b_{i2}z^{-2} + \dots + b_{im}z^{-m} \quad i=1,2,3 \\ C(z^{-1}) & ? c_0 + c_1z^{-1} + c_2z^{-2} + \dots + c_{np}z^{-n} \end{aligned} \quad (4)$$

$A, B_1, B_2, B_3$  and  $C$  are polynomials of an appropriate order in the difference (or delay) operator  $z^{-1}$  (where  $z^{-1}F(t)=F(t-1)$  with  $T$  being the sampling interval) and  $k_1, k_2, k_3$  and  $k_e$  are

the dead times associated with the four terms in Equation (3). The fourth term  $e_1$  is a white noise process to represent the stochastic. The scalar term  $d$  is a DC term.

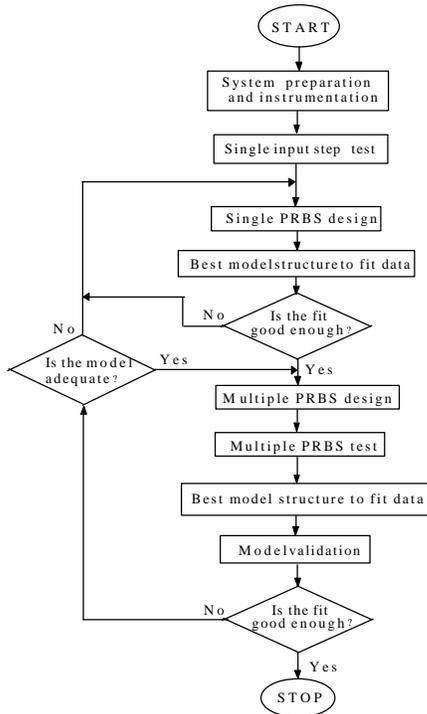


FIGURE. 3  
BASIC MODELING PROCEDURE

A similar expression may be written for the temperature of the air in the other zone of the test cell. Fitting this type of model to the system, therefore, involves determining those coefficients in the  $A$ ,  $B_i$  and  $C$  polynomials that give the best fit to measured data.

Obtaining suitable data for modeling purposes is itself a specialized activity and requires considerable care [8]. A good discussion of how to obtain good data to model this system can be found in several references [9]-[11]. The key element here is to obtain data, which are representative of the important operating modes of the system under study. However, the modeling can be carried out according to the procedure shown in Figure 3. This procedure is based on pseudo random binary sequence testing, which is explained in detail in reference [11]. The algorithms used is based on recursive least squares and enable the identification of a whole family of parametric model structures ranging from autoregressive to the fully blown structures; in our particular case an Auto-Regressive Moving Average with exogenous inputs. The moving average refers to the fact that the process is affected by non-white stochastic disturbances.

The identification of the model shown in Equation (3) is implemented by available least squares based routines available in a MATLAB. For this purpose and for ease of computation, the data collected from the system has to be arranged by defining a vector of model parameters, and input-output and error measurements resulting in:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_i \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} A_{i,1} & A_{i,2} & \dots & A_{i,m} \\ B_{i,1} & B_{i,2} & \dots & B_{i,n} \\ C_{i,1} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \\ e \end{bmatrix} + d \quad (5)$$

where,  $N$  is the number of observations,  $T$  the sampling interval,  $A_{i,j}^*$  the auto-regressive polynomial (for output  $D$ ),  $A_{i,j}$  ( $j \neq i$ ) the cross-coupling polynomials (from other outputs), and  $B_{i,j}$  and  $C_{i,i}$  are the parameters for the exogeneous and noise inputs, respectively. Notice that model from Equation 1 has been re-written in a set of multi inputs single output models, one of which is that shown in Equation 5 (for output  $i$ ). These equations can be solved by using a least-squares criterion to fit

an optimal parameter set to the observed data by using the following equation.

$$\begin{bmatrix} Y_i \\ Y_i \\ \vdots \\ Y_i \end{bmatrix} = \begin{bmatrix} A_{i,1} & A_{i,2} & \dots & A_{i,m} \\ B_{i,1} & B_{i,2} & \dots & B_{i,n} \\ C_{i,1} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \\ e \end{bmatrix} + d \quad (6)$$

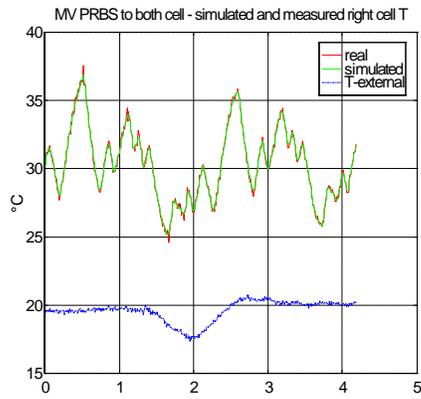
This was carried out on the measured input-output data using the MATLAB and the System Identification Toolbox.

**MODEL FOR THE TEST-CELL**

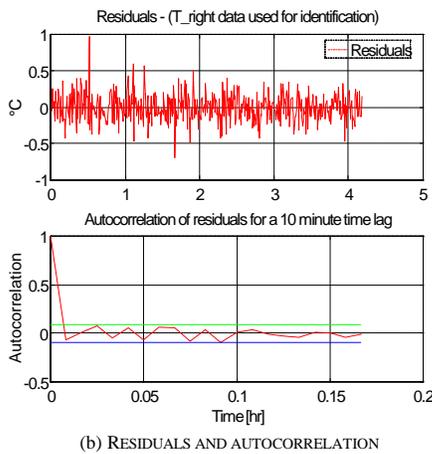
The modeling exercise would typically be carried out by the student in accordance with the procedure outlined in Figure 3. They would be expected to present an output equation similar to the following difference equation shown in Equation 7, which can be used to obtain temperature for both the chambers.

$$A \cdot T_1 + B \cdot T_2 + W_1 \cdot W_2 \cdot T_{ext} = C \cdot e(t) \quad (7)$$

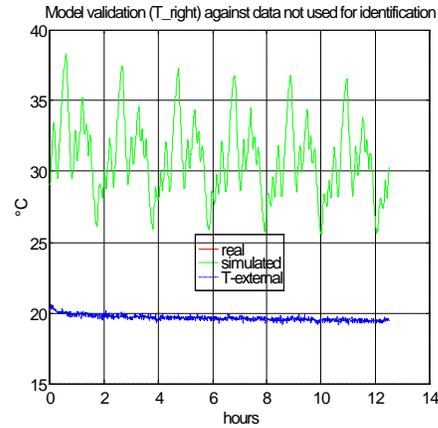
The developed batch model is then validated for accuracy. The validation outcome is shown through Figures 4(a) to (d). First against the set of data used to derive the model (Figures 4(a) and 4(b)), then against data, which was not used in the derivation of the model (Figures 4(c) and 4(d)). In this particular case, results indicate that the model is able to predict air temperature to well within 0.5°C.



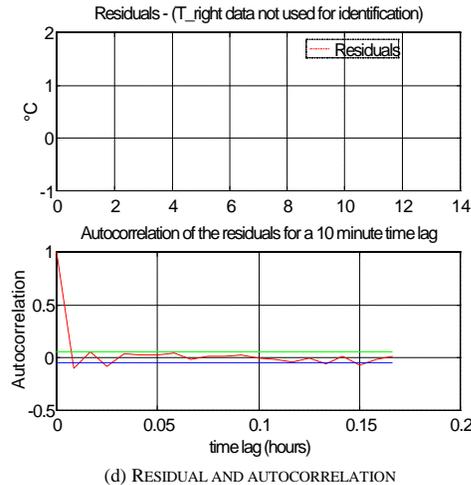
(a) AGAINST DATA USED FOR IDENTIFICATION



(b) RESIDUALS AND AUTOCORRELATION



(c) AGAINST DATA NOT USED FOR IDENTIFICATION



(d) RESIDUAL AND AUTOCORRELATION

**FIGURE. 4**  
MODEL VALIDATION.

Having obtained a model, which can describe the air temperatures in the two halves of the test cell, it is useful to consider possible uses of the models. The student can use the identified model to test different controller designs before implementing them on the real system. Another alternative is for the student to use the identified structure to implement an on-line adaptive model, which can then be used in a predictive fashion for control purposes.

**FLEXIBLE ROBOTIC MANIPULATOR SYSTEMS**

The demand for the employment of robots in various applications has increased in line with the increasing demand for system automation. The dominant factor that contributes largely to performance limitations of the robot is the limited capability of its control system, especially in applications requiring high speed and/or large payloads.

The need for lightweight elastic robot manipulators has increased, as they are capable of improving the speed of operation and handling larger payloads in comparison to rigid manipulators with the same actuator capabilities. Considering these, there has been a growing interest in using flexible manipulators at a rapid pace in recent years. The other advantages are lighter weight, low power consumption, compliant structure, possible elimination of gearing, low mounting strength, safer operation and faster response. However, the major drawback of flexible manipulators is their vibration arising from lightweight physical structure while in fast motion. This problem has traditionally been solved by mechanically stiffening the manipulator. However, this leads to an increase in the weight of the manipulator. Thus, a conventional robot manipulator does not achieve the objective of the lighter weight requirement of the flexible manipulator.

It is important initially to recognize the flexible nature of the manipulator and construct a mathematical model for the system that accounts for the interactions with actuators and payload. The commonly used approaches for computer simulation of flexible manipulator systems are finite element (FE) and finite difference (FD) [12]-[14]. The computational complexity and consequent software coding involved in the FE method is a major disadvantage of this technique. However, as the FE method allows irregularities in the structure and mixed boundary conditions to be handled, it is found suitable in applications involving irregular structures. In applications involving uniform structures, such as the manipulator system considered here, the FD method is found to be more appropriate [15].

**CASE-2: FLEXIBLE ROBOTIC MANIPULATOR SYSTEM**

The area of flexible robotic manipulators is also a challenging problem that requires the students to understand vibration behavior of a structure along with its various co-ordinate systems. This requires the partial differential equation (PDE) to describe system's behavior as well as its solution towards the development of a simulation environment [16]. These are extremely complex issues and newcomers can get confused very easily.

The flexible manipulator systems range from single-link manipulator rotating about a fixed axis to three-dimensional multi-link arms. However, experimental work, in general, is almost exclusively limited to single-link manipulators. This is due to the complexity of multi-link manipulator systems, resulting from more degrees of freedom and the increased interactions between gross and deformed

motions. Even the single-link flexible manipulator are too complicated to bring into the classroom environment. To handle this problem a prototype experimental system has been developed to represent a single-link flexible manipulator system. A computer simulation environment has also been developed through this initiative.

**THE SYSTEM**

The flexible manipulator system under consideration is modeled as a pinned-free flexible beam, with a mass at the hub. This beam can bend freely in the horizontal plane but is stiff in vertical bending and torsion. To avoid the difficulties arising due to time varying length, the length of the manipulator is assumed to be constant.

A schematic representation of the manipulator with a moment of inertia  $I_b$ , hub inertia  $I_h$ , a linear mass density  $\rho$  and a length of  $l$  is shown in Figure 5. The payload mass is  $M_p$  and  $I_p$  is the inertia associated with the payload. A control torque  $\tau(t)$  is applied at the hub of the manipulator by an actuator motor. The angular displacement of the manipulator, in moving in the  $POQ$  plane, is denoted by  $\theta(t)$ . The width of the arm is assumed to be much greater than its thickness, thus allowing the manipulator to vibrate (be flexible) dominantly in the horizontal direction. The shear deformation and rotary inertia effects are also ignored.

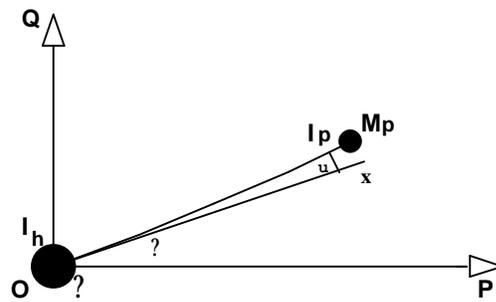


FIGURE. 5  
SCHEMATIC REPRESENTATION OF THE FLEXIBLE MANIPULATOR SYSTEM.

For an angular displacement  $\theta$  and an elastic deflection  $u$ , the total (net) displacement  $y(x,t)$  of a point along the manipulator at a distance  $x$  from the hub can be described as a function of both the rigid body motion  $\theta(t)$  and elastic deflection  $u(x,t)$  measured from the line  $OX$ .

$$y(x,t) = x\theta(t) + u(x,t) \tag{8}$$

To obtain equations of motion of the manipulator, the

associated energies (kinetic, potential and dissipated energies) have to be obtained. Thus, using the Hamiltonian's Extended Method, the dynamic equation of the flexible manipulator with the associated boundary and initial conditions can be expressed as [16]

$$EI \frac{\partial^4 y(x,t)}{\partial x^4} + \rho \frac{\partial^2 y(x,t)}{\partial t^2} - D_s \frac{\partial^3 y(x,t)}{\partial x^2 \partial t} = \tau(t) \quad (9)$$

$$\begin{aligned} I_h \frac{\partial^3 y(0,t)}{\partial t^2 \partial x} &= EI \frac{\partial^2 y(0,t)}{\partial x^2} \tau(t) \\ M_p \frac{\partial^2 y(l,t)}{\partial x^2} &= EI \frac{\partial^3 y(l,t)}{\partial x^3} \\ I_p \frac{\partial^3 y(l,t)}{\partial t^2 \partial x} &= EI \frac{\partial^2 y(l,t)}{\partial x^2} \\ y(x,0) &= 0, \quad \frac{\partial y(x,0)}{\partial x} = 0 \end{aligned} \quad (10)$$

where,  $E$  is the Young Modulus,  $I$  is the second moment of inertia of the manipulator and  $\tau(x,t)$  is the applied torque. For the system under consideration, the torque  $\tau(x,t)$  is applied at the hub of the manipulator; therefore, it can be represented as  $\tau(0,t)$  or simply  $\tau(t)$ .

**ALGORITHM DEVELOPMENT**

The PDE in equation (9) describing the flexible manipulator system is of a hyperbolic type and can be classified as a boundary value problem. This can be solved using an FD method [17]. This involves dividing the arm into a finite number of equal-length sections and developing a linear difference equation describing the deflection of the end of each section (grid-point). Thus, using the FD method, a solution of the partial differential equation (9) can be obtained as [18]:

$$\begin{aligned} y_{i,j+1} &= \frac{\tau^2}{2} a_{i,j} + c_{i,j} y_{i+2,j} + b_{i,j} y_{i+1,j} + y_{i,j} \\ &+ a_{i,j} y_{i,j+1} + d_{i,j} y_{i+1,j} + 2y_{i,j} + y_{i+1,j} \\ &+ y_{i+1,j+1} + 2y_{i,j+1} + y_{i+1,j+1} \end{aligned} \quad (11)$$

where,

$$a = 2 - \frac{6EI\tau^2}{\rho x^4}; b = \frac{4EI\tau^2}{\rho x^4}; c = \frac{EI\tau^2}{\rho x^4}; d = \frac{D_s\tau}{\rho x^2} \quad (12)$$

Equation (11) gives the displacement of section  $i$  of the manipulator at time step  $j + 1$ . It follows from

this equation that, to obtain the displacements  $y_{n+1,j+1}$  and  $y_{n,j+1}$ , the displacements of the fictitious points  $y_{n+2,j}$ ,  $y_{n+1,j}$  and  $y_{n,j+1}$  are required. These fictitious displacements can be obtained using the boundary conditions related to the dynamic equation of the flexible manipulator. The discrete form of the corresponding boundary conditions, obtained in a similar manner as above are

$$\begin{aligned} y_{0,j} &= 0 \\ y_{-1,j} &= y_{1,j} + \frac{xI_h}{EI\tau^2} y_{1,j+1} - 2y_{1,j} + y_{1,j-1} \\ &+ \frac{\tau^2}{EI} \tau(j) \\ y_{n+2,j} &= 2y_{n+1,j} - 2y_{n-1,j} + y_{n-2,j} + \\ &\frac{2x^3 M_p}{\tau^2 EI} y_{n,j+1} - 2y_{n,j} + y_{n,j-1} \end{aligned}$$

$$y_{n+1,j} = 2y_{n,j} - y_{n-1,j} \quad (13)$$

Manipulating equation (11) using equations (12) to (13) yields a matrix formulation of the above as

$$\mathbf{Y}_{i,j+1} = \mathbf{A}\mathbf{Y}_{i,j} + \mathbf{B}\mathbf{Y}_{i+1,j} + \mathbf{C}\mathbf{F} \quad (14)$$

where  $\mathbf{Y}_{i,k}$  is the displacement of grid points  $i = 1, 2, \dots, n$  of the manipulator at time step  $k$  ( $k = j + 1, j, j - 1$ ).  $\mathbf{A}$  and  $\mathbf{B}$  are constant  $n \times n$  matrices whose entries depend on the flexible manipulator specification and the number of sections the manipulator is divided into,  $\mathbf{C}$  is a constant matrix related to the time step  $\tau$  and mass per unit length of the flexible manipulator, and  $\mathbf{F}$  is an  $n \times 1$  matrix related to the given input torque. Equation (14) thus represents the dynamic equation of the manipulator in the presence of hub-inertia and payload, which is then implemented on a computer to develop a simulation environment.

**EXPERIMENTAL SYSTEM**

An experimental prototype system has also been developed to demonstrate the system's behavior along with the verification of the developed simulation environment. A schematic diagram of the designed experimental rig is shown in Figure 6. The shaft encoder is used for measuring the hub angle of the manipulator. A tachometer is used for measurement of the hub velocity. An accelerometer is located at the end-point of the flexible arm, measuring the end-point acceleration. The flexible arm is constructed using a piece of thin aluminum alloy. The physical parameters of the flexible arm are given in Table 1.

It has been reported that the vibration of the flexible arm is dominated by the first few resonance modes [19]. For this purpose the first three resonance modes are considered in this investigation. The response of the flexible manipulator is monitored and obtained by utilizing low-pass filters to limit the frequency modes up to the first three modes and to reject the unwanted higher modes. Anti-aliasing filters with cutoff frequency of 100 Hz are used for the four outputs namely, the hub-angle output, the hub-velocity output, the end-point acceleration output and the motor current amplifier output.

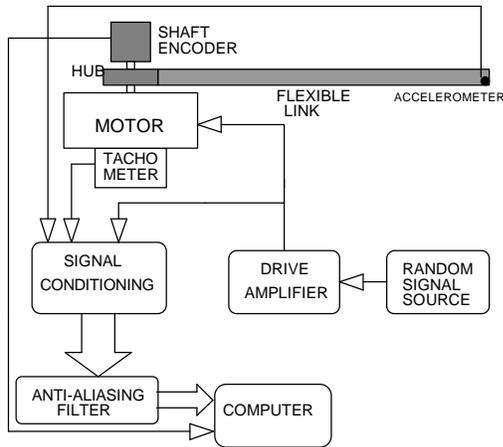


FIGURE 6.

SCHEMATIC DIAGRAM OF THE FLEXIBLE MANIPULATOR SYSTEM.

TABLE 1

PARAMETERS AND CHARACTERISTICS OF THE FLEXIBLE MANIPULATOR SYSTEM.

Parameter	Value	Parameter	Value
Length	960.0 mm	Second moment of inertia	$5.19 \times 10^{11} \text{ m}^4$
Width	19.00 mm	Young modulus	$71 \cdot 10^9 \text{ Nm}^{-2}$
Thickness	3.20 mm	Moment of inertia	$0.048 \text{ kgm}^2$
Mass density /unit volume	$2710 \text{ kgm}^{-3}$	Hub inertia	$5.86 \cdot 10^{24} \text{ kgm}^2$

**SIMULATION ENVIRONMENT**

To study the behavior of a flexible manipulator system and testing the performance of controller designs, a SIMULINK library (ALIBRARY.M) was constructed to

help the user to develop his/her own system with various input torque and controllers [20]. This was done by implementing the developed algorithm within the MATLAB and SIMULINK environments. In addition to the flexible manipulator system, several conventional open-loop and closed-loop controllers are also provided. Figure 7 shows the SIMULINK library for the flexible manipulator system with various related functions. A brief description of the various icons in Figure 7 is given below.

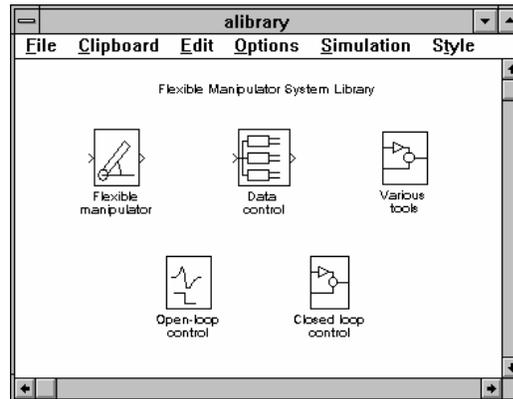


FIGURE. 7

SIMULINK LIBRARY FOR SIMULATION AND CONTROL OF THE FLEXIBLE MANIPULATOR SYSTEM.

**Flexible Manipulator:** Simulates the flexible manipulator with any given physical dimensions and characteristics. These can either be specified by the user or the predefined default values given in Table-1 can be used. This uses the matrix form of the FD implementation method.

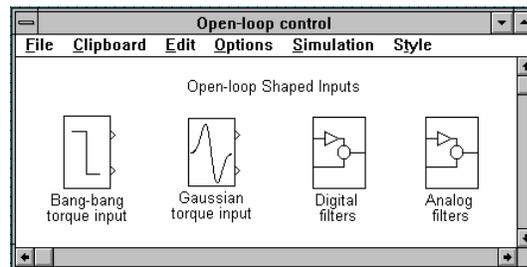


FIGURE. 8

LIBRARY OF OPEN-LOOP SHAPED INPUTS.

**Open-loop Control:** Subgroup of various shaped torque signals, such as Gaussian shaped, low-pass and band-stop filter both analog and digital type (Figure 8). By using these shaped inputs, input torque profiles are developed that minimize input energy at system natural frequencies, and the flexible manipulator's vibration during and after a

movement is reduced.

**Closed-loop control:** Subgroup of two closed-loop control strategies (see Figure 9), namely, a joint based collocated proportional derivative (PD) controller and a hybrid collocated and non-collocated type controller.

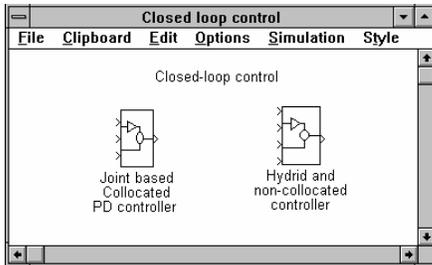


FIGURE. 9

CLOSED-LOOP CONTROL STRATEGIES FOR THE FLEXIBLE MANIPULATOR SYSTEM.

The collocated type control incorporates hub position and hub velocity information for the controller design. The designed controller will attenuate the first three dominant modes of the flexible manipulator. In the hybrid collocated and non-collocated type, the control structure utilized has two feedback loops: one using the filtered end-point acceleration as input to a control law, and the other using the hub displacement and hub velocity as input to a separate control law. These two loops are then summed, and the result passed through the amplifier/motor gain to produce torque input to the manipulator. The first loop that comprises the hub displacement and hub velocity signal is considered as the rigid body motion control loop. Using the end-point acceleration feedback through a PID controller controls the flexible motion of the manipulator. The values of proportional, derivative and integral gains as indicated earlier, are adjusted using the Ziegler-Nichols Tuning Method [21].

**OPEN-LOOP RESPONSE OF A FLEXIBLE MANIPULATOR**

The use of the developed simulation environment is demonstrated through the formulation of a test case to observe the open-loop response of a flexible robot manipulator system. The developed model is shown in Figure 10.

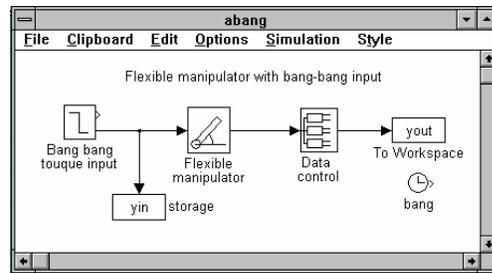


FIGURE. 10

FLEXIBLE MANIPULATOR WITH BANG-BANG INPUT TORQUE.

The input and outputs are stored in the MATLAB workspace. These can subsequently be used for monitoring and documentation. Stored input and outputs of the system and their spectra can be observed by using a suitable graphical user interface (GUI). This GUI will guide the user through various options and display the required output in a MATLAB figure window.

System input and various outputs from the above simulated system and their spectral analysis obtained through this process are shown in Figures 11 to 16.

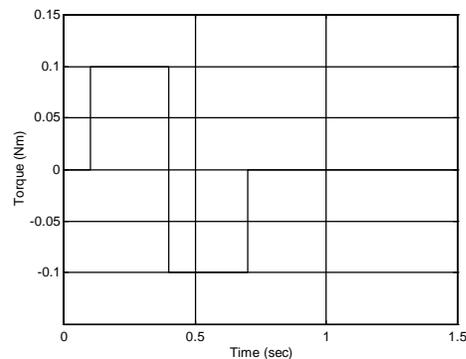
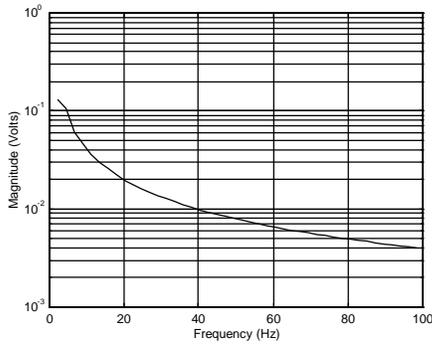


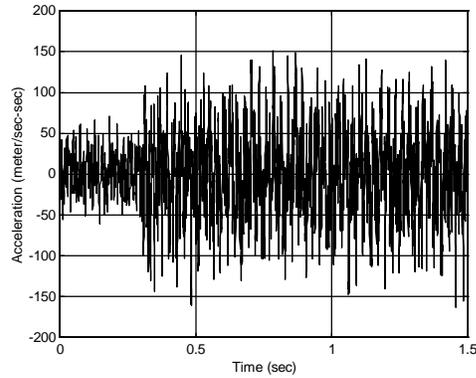
FIGURE. 11

BANG-BANG TORQUE INPUT TO THE FLEXIBLE MANIPULATOR SYSTEM.

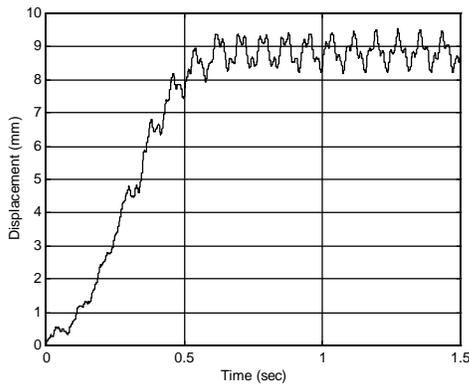
Figure 11 and Figure 12 are showing the torque input and its spectral behavior. Figure 13 is showing the displacement at the hub point, while Figure 14 represents the spectral behavior of hub point displacement showing first three resonant frequencies. These are at around 16Hz, 39Hz and 75 Hz. The end-point acceleration is presented in Figure 15 with its frequency spectrum in Figure 16. The resonant frequencies in this case are also in the similar range.



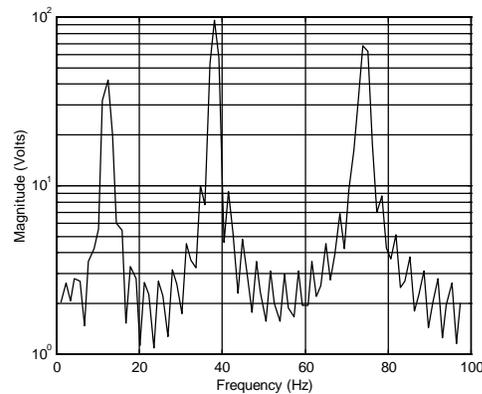
**FIGURE. 12**  
SPECTRAL DENSITY OF THE BANG-BANG TORQUE INPUT.



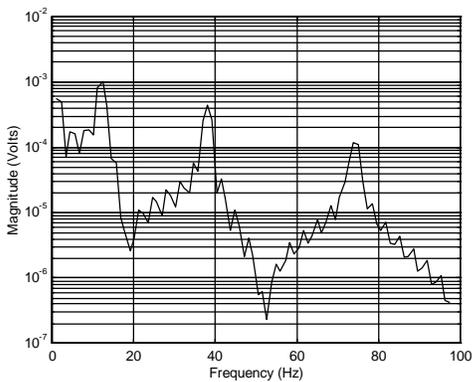
**FIGURE. 15**  
END-POINT ACCELERATION WITH BANG-BANG TORQUE INPUT.



**FIGURE. 13**  
HUB DISPLACEMENT WITH BANG-BANG TORQUE INPUT



**FIGURE. 16**  
SPECTRAL DENSITY OF THE END-POINT ACCELERATION WITH BANG-BANG TORQUE INPUT.



**FIGURE. 14**  
SPECTRAL DENSITY OF HUB DISPLACEMENT SIGNAL WITH BANG-BANG TORQUE INPUT.

### CONCLUSIONS

The development of computer modeling and simulations for simplified version of complex engineering systems has been presented. This is also accompanied with prototypes so that the developed model and simulation outcomes can be verified for confidence. Both systems have proven to be valuable educational tool for understanding the behavior of the systems under consideration.

In case of building services system, a model describing the variations of air temperature inside a two-zone test cell has been derived. The results produced are promising and warrant the work, which is being carried out on the two-zone test cell. It is expected that the methodologies developed on the lab-scale system will be portable to larger systems.

The flexible manipulator simulation environment and the prototype system can be utilized to investigate various

other aspects of active vibration control in flexible manipulator systems. Users can design their own SIMULINK blocks and couple them with specific requirements. In this manner, the incorporation of closed-loop control methods of fixed and adaptive nature are currently being investigated by the authors. In addition to this, a data analysis provision is also provided through a GUI within the package to enable users to analyze their data obtained from a test run. This makes the environment user-friendly and saves the time and effort to transfer the data to another environment for analysis.

Both of the reported systems are currently being utilized towards engineering graduate programs at the University of Sheffield and University of Portsmouth; both of them are in the UK. The experience shows that these simple and realistic experimental systems along with computer modeling and simulation allow students to be much more receptive towards solving the underlying theoretical problems.

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