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Development of Experimental Setup to Validate Bond Graph Modelling of Two Stage Reciprocating Air Compressor with Intercooler

#1Mr. Rahil Pujara, #2Mr. Sagar R. Bhave, #3Mr. Sachin A. Kulkarni

[1]rahilpujara@gmail.com

[2]srbhave.scoe@sinhgad.edu

[3]sakulkarni.scoe@sinhgad.edu

#123Sinhgad College of Engineering,

ABSTRACT

The Bond Graph (BG) modelling of multi domain system is the main objective of the proposed work. The BG model of two stage air compressor without intercooler is developed further as model with intercooler. The experimental validation is an essential component to support the theme proposed. The instrumentation to measure intercooler temperatures, variation in low pressure cylinder pressure, second stage outlet pressure, mass flow rate, and energy meter were added to the air compressor. The sensor data is collected using the data acquisition system (DAS) NI cDAQ9219. This DAS is configured with the LabVIEW to design the appropriate control panel. The setup consists of various channel outputs from the DAS of NI cDAQ9219 to workout various efficiencies, the variation in temperature and drop in pressure in the intercooler with respect to time. The time plots of sensors are displayed using specifically built Graphical User Interface (GUI) with LabVIEW to showcases the required results of calculations. This setup finally not only confirms the output performance of BG model of air compressor but also endorse the proposed procedure to systematically map the physical process in Bond Graph.

Keywords— **Bond Graph, Intercooler, Model, cDAQ9219, critical pressure, cylinder pressure variation**

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I. INTRODUCTION

In the recent era, optimized and efficient automation of compressor test rig is a vital key to derive and analyse the energy consumption and also the performance monitoring to assess the workability of the newly designed and assembled compressor system. New technologies in this automation have emerged, which requires significantly less expertise and also reduction in manpower to avoid difficult tasks and controlling the operation of compressor, to maintain the system uprightness, reliability and the cost associated with it.

The performance testing of a compressor is very important to evaluate its present working conditions, actual response of temperature and pressure transducers applied. The demonstrated analysis helps in indicating any physical condition such as fouling, internal wearing and also presence of any uncontrolled environment. Hence it is of utmost importance to obtain the accurate performance data in the field with the necessary instrumentation with a fairly acceptable uncertainty within the measurement limits.

The Bond Graph (BG) modelling is especially useful to map the power input till output in respective domains. It also derives the important conclusions about the intermediate values of the variables of interest. The optimization is one of the projected application after the successful simulation of the model.

The single stage air compressor model was already proved. The present work has a quick mention of two stage air compressor with intercooler. To validate the work, the air compressor is upgraded which confirms the success of the BG model proposed.

II BOND GRAPH MODEL OF SINGLE STAGE RECIPROCATING AIR COMPRESSOR

In this dissertation work, the simulation is obtained with the help of first principles as against only governing differential equations. The BG simulation, variables are required to be power variables i.e. effort andflow and so is maintained domain specific, while modelling.

The abstract mathematical representation proves to be complex to develop and difficult to implement. The block diagram representation, single variable flows across, and block quantities represent component and/or subsystem. The BG model represents both signal flow and various domains are also indicated along with signal flow. Figure 1 shows the BG model of single stage reciprocating air compressor.[1]The Sf represents angular velocity of motor, is stepped down by 2 throughTF which represents reduction through V belt pulleys. This is converted into linear velocity through the slider crank mechanism.. The linear velocity of piston is taken in y direction. The element *Piston*converts this linear velocity into rate of change of volume by multiplying this velocity by area of piston followed by integrating it in the *C*element to work out pressure generated in the cylinder of the compressor. This is the first domain change from mechanical to thermal. This pressure is acts on the piston and *Piston* element estimates the force, which travels back to Sf to feedback the effort i.e. torque in this case.

The component of this force perpendicular to the cylinder causes friction at the wall of the cylinder tis generates heat flow. Some of this generated heat flow is stored in the fins of the cylinder and some of heat is given to the atmosphere. The storage of heat causes increase in the temperature of fins this represented by *C* element and the heat dissipated to the atmosphere is represented by *R* element this is nothing but convection process. The *Se* element stands for atmospheric temperature.

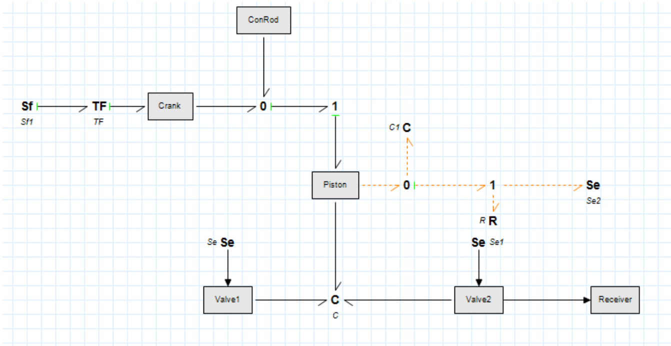

Fig.1 Bond Graph modeling of single stage reciprocating air compressor

III ADDING SECOND STAGE AND INTERCOOLER

The elements of single cylinder air compressor are imploded as shown in Fig 2. The *Piston*, *C*, *valve1* and *valve2* are imploded in the *Cylinder1*. The *Cylinder1* gives massflow to the *Cylinder2* and takes pressure from it. This forms the pseudo-pneumatic domain The *Cylinder2* shown appended here, which is replica of *Cylinder1*with the only change is the parameters. The piston velocity of both cylinder is same and the torque generated at the crank is the addition of effect at both the piston hence they are connected by *1* junction. In the *Cylinder1* the pressure as well as temperature increases. This increased temperature which directly affects work done. To cool the air between low pressure cylinder and high pressure cylinder the *Intercooler* is added. The *Intercooler*has input as temperature and gives enthalpy to the *C* element in the *Cylinder1*. This is second domain change from pseudo-pneumatic to thermal. The temperature reduced is applied as signal to the *C* element of *Cylinder2*, finally *Cylinder2* gives the massflow signal to the receiver.

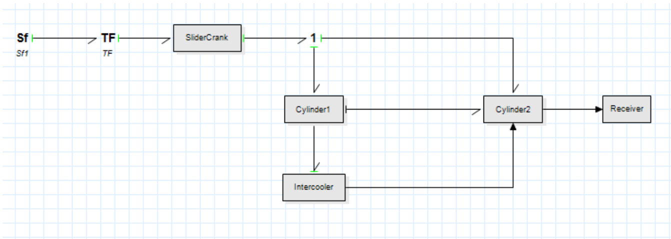

Fig.2 Bond Graph modeling of two stage reciprocating air compressor

III SIMULATION RESULTS

The simulation is done for considering ideal condition Fig. 3 shows the pressure with respect to time. The simulation is done for 2 cycles. It is seen that during compression and expansion polytrophic process takes place and when valve open or closes constant pressure process takes place. The outlet pressure of the LPC is 1.9 Bar and inlet pressure is atmospheric.

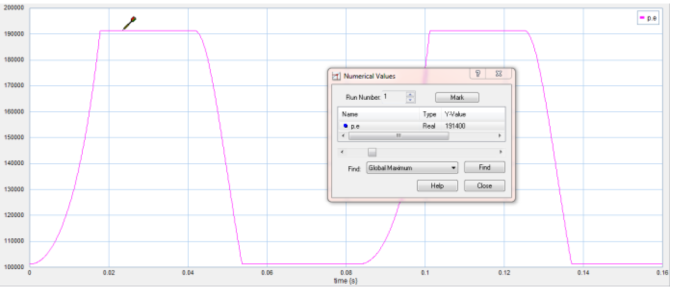

Fig. 3 Pressure variation with respect to time

Figure 4 shows the variation of temperature at the fins of low pressure cylinder. Simulation is done for 50 minutes. It is seen that the temperature increases from atmospheric to 55 ^{0}C in 15 minutes after that it will remain constant

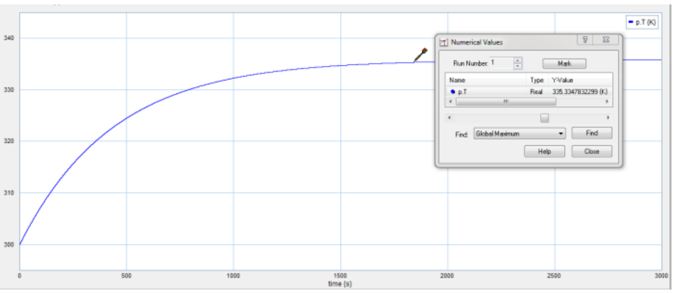

Fig. 4 Temperature at the fins of the LPC

Figure 5 shows the temperature variation at the outlet of intercooler simulation is done for 10 seconds it is seen that initially temperature is 338 ^{0}K In few seconds' temperature decreases gradually and outlet temperature is 312 ^{0}K. The temperature of air decreases by 26 ^{0}C .

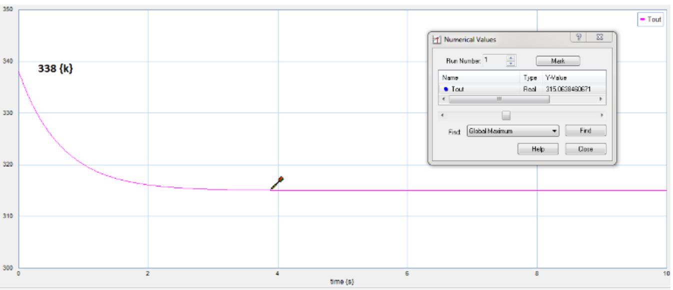

Fig. 5 Temperature variation at the outlet of intercooler

IV TEST SETUP

To compare these simulation results the available compressor in the thermodynamics lab is upgraded. The various sensors are installed on air compressor to measure temperature, pressure, mass flowrate etc. These parameters are further used for calculating efficiencies of air compressor. At inlet of air-compressor "Sitrans" mass flowmeter MASSFLO MASS 2100 is mounted. The sensor provides 4 – 20 mA signal proportional to mass flow rate as per the selected range.

The K type thermocouples are mounted for temperature measurement at outlet and inlet of low pressure cylinder and high pressure cylinder respectively. These thermocouples give temperatures across intercooler so as to record temperature drop across intercooler. The outputs of these thermocouples are acquired through NI cDAQ as well as displayed on control panel.

WIKA A-10 pressure transmitter is mounted on low pressure cylinder to transmit pressure to display and the DAQ system. FESTO's differential pressure sensor is mounted at outlet of high pressure cylinder and on the tank to record the outlet valve behavior and nature of accumulating air in the reservoir. The pressure gauge mounted on the storage tank gives pressure inside the tank along-with temperature sensor is mounted to measure temperature of compressed air in the tank.

The output signal from this all sensors are given to the data acquisition system NI cDAQ 9219, to transfer all to the LabVIEW software.

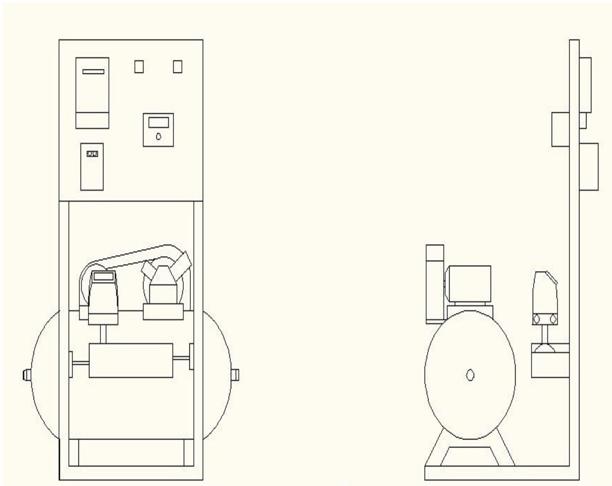

Fig.6 Test Setup

A Technical specifications of Test Rig

(i) Compressor specifications:

- Bore of low pressure (L.P.) cylinder, D_{LP}= 76 mm
- Bore of high pressure (H.P.) cylinder, D_{HP}=44 mm
- Stroke of L.P. cylinder, $L_{LP=}$70mm
- Stroke of H.P. cylinder, $L_{HP=}$70mm
- Rated speed= 635rpm
- Maximum working pressure=6.25 bar
- Air receiver capacity= 0.04677 m^3

(ii) Motor Specifications:

- Power=1.5 KW
- Electrical Supply =3ϕ
- Rated speed=1458 rpm

(iii) Other Specifications:

- Diameter of motor pulley, D1= 15mm
- Diameter of compressor pulley, D2= 35mm

B.LabView

The NI LABVIEW is a graphical programming language (named as "G" code) designed for engineers and scientists to develop test, control, and measurement applications. TheGraphical system designis a modern approach to designing, prototyping, and deploying embedded systems which combines open graphical programming with hardware to dramatically simplify development.

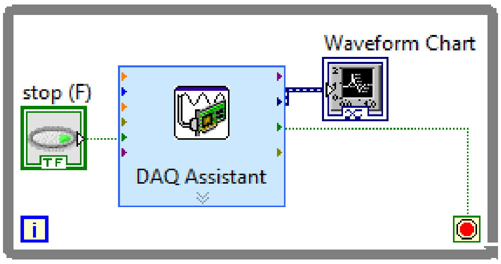

Fig.7 : DAQ Configuration

The Figure 7 indicates the DAQ configuration. This is to acquire the analog voltage signals from the pressure and temperature transmitters. The LABVIEW is a system-design platform and development environment for a visual programming language.

V RESULTS AND DISCUSSION

The observations are taken on LabView and gauges which are installed on the air compressor. The Simulation results matches with the observation

TABLE I
OBSERVATION TABLE

Sr. No.	Particulars	Notations	Unit	Reading
1	Intake pressure	P_1	Bar	1
2	Intermediate pressure	P_2	Bar	1.9
3	Delivery pressure	P_3	Bar	6.25
4	Intake temperature	T_1	K	300
5	Temperature before intercooler	T_2	K	328
6	Temperature after intercooler	T_3	K	310
7	Delivery temperature	T_4	K	348
8	Motor speed	N_1	rpm	1458
9	Density of air	P	Kg/m^3	1.035
10	Mass flow rate	Q	Kg/s	0.002
11	Volume flow rate		m^3/s	0.00193

Figure 8 shows the pressure waves the LPC. The amplitude of the pressure varies between 1 to 3. The pressure is calibrated in the form of voltage. 3 volts stands for 2 bar pressure. Figure 8 shows the actual pressure wave. If it is compared with ideal pressure wave which is shown in figure 3 it is seen that the amplitude of pressure matches and compression and expansion lines are in excellent agreement with the ideal one. But when inlet and exhaust valve opens it differs with the ideal one since when valve opens before TDC during compression so that during this motion of piston the pressure increases continuously. In case of expansion the valve opens after BDC so that there is some deflection of pressure takes place.

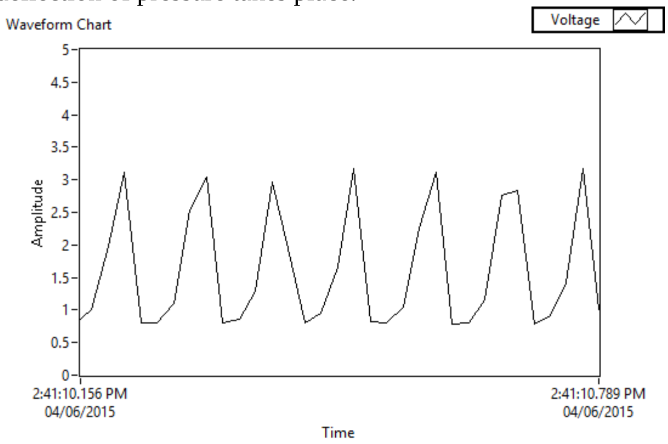

Fig. 8 Pressure plot at LPC

The temperature in low pressure cylinder rises due to compression process. The air is sucked in during suction stroke which is compressed polytropically with polytropic index 1.21. At initial stage this temperature increases gradually up to particular maximum value and then remains constant due dissipations of heat through fins over low pressure cylinder. The temperature rise observed by thermal imager is about 58˚C - 60˚C. Figure 8 shows temperature distribution across cylinder. Figure 9 shows temperature distribution across fin of low pressure cylinder. From graph it is observed that temperature is maximum at central part while it decreases as it goes away from central part. The temperature of fins exactly matches with the simulation results shown in figure 4.

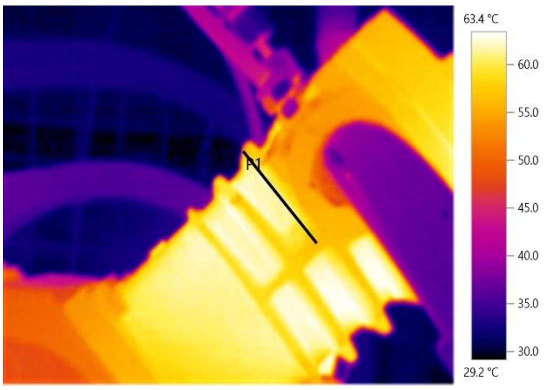

Fig. 8 temperature distribution across low pressure cylinder

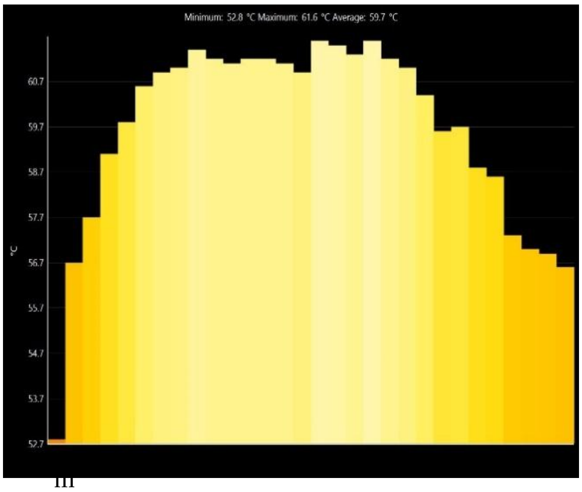

Fig.9 temperature distribution across low pressure cylinder fin

The temperature at inlet of intercooler is temperature rise due to pressure rise in low pressure cylinder temperature. Figure 9 shows temperature rise with respect to time. As per observation temperature at intercooler was raised up to 55˚C and onward was approximately constant at 55˚C.

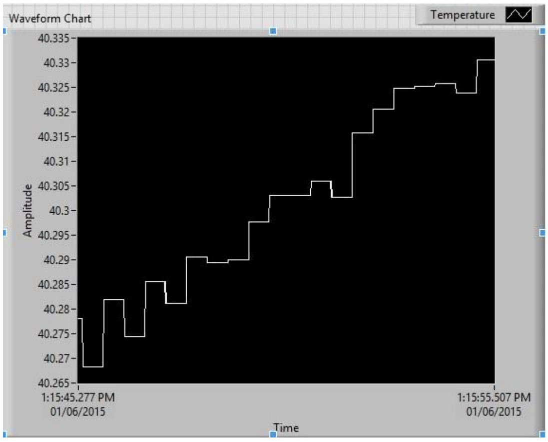

Fig. 10 temperature variation at inlet of intercooler with respect to time

Temperature rise observer by thermal imager is about 55˚C - 60˚C. Figure 10shows temperature distribution at the inlet of the intercooler. Intercooler outlet temperature is temperature at inlet of high pressure cylinder. In ideal condition of intercooling or in case of perfect cooling temperature after intercooling is equal to that of inlet temperature or suction temperature. But in practical application perfect cooling is impossible. During observation it was observed that there was drop of approximate 18˚C - 19˚C across intercooler. Figure 12 shows variation of temperature with respect to time which shows that temperature remains almost constant at 37˚C. Figure 12 shows temperature distribution at outlet of inter cool er.

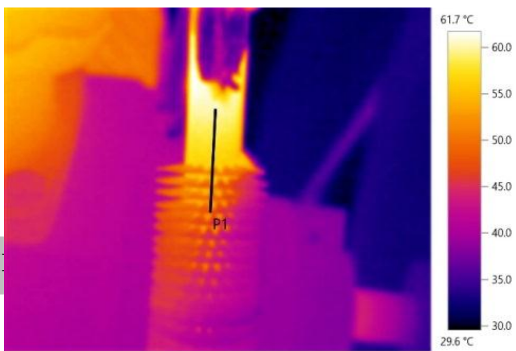

Fig. 11 temperature variation at outlet of intercooler with respect to time

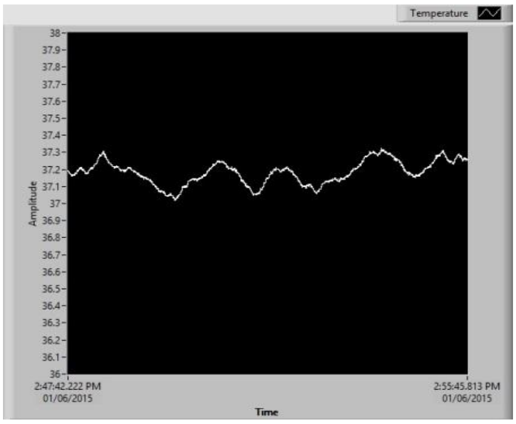

Fig. 12: Temperature distribution at outlet of intercooler

The comparison ofexperimental results with the simulation results of the intercooler shown in figure 5, revels that the temperature in the intercooler decrease from 65 ^{0}C to 39 ^{0}C. The temperature decreases by 26 ^{0}C in few seconds it is in excellent agreement with experimental results

VI CONCLUSION

The BG simulation of two stage intercooled air compressor is discussed initially. This dissertation work basically aims to bring up a set up which will support the results of the simulation. The main reasons to bring up the set up were

1. The educational setups available did not have provision to measure the cylinder pressure. All setups the pressure sensor/ gauge is mounted at the outlet of the cylinder. This does not show the pressure variation in the cylinder.
2. All the setups had no provision to measure the mass flow rate. It was concluded from orifice meter attached at inlet of the compressor.
3. In any of the setup the variation/ nature of the signal of pressure, temperature, etc., was not possible with respect to time.

The BG model requires all the parameters to be plotted with respect to time as results of simulation are. The comparison of the plots revels that

1. The compressor cylinder pressure is perfectly theoretical and actual does not match with it. This is because, the pressure transducer was not exactly in clearance volume and clearance volume is increased than considered.

2. Again when the outlet valve opens, then some of the mass goes out but not so enough drive mass of air out at same pressure. Therefore some pressure rise is seen after the exhaust valve is opened.
3. The air temperature in the cylinder is found increasing when outlet valve of the tank is open partially. But it decreases drastically when the valve is closed. This confirms the BG results of the model proposed.
4. The temperature distribution across the fins was not the objective of the set up in the present context. This is incorporated as future scope. When the BG model shall have provision to model the heat generated because of piston friction and temperature of air inside the cylinder, these results shall prove to be a value.
5. The BG model is not discussed fully as the scope was to develop a test rig for air compressor.

REFERENCES

1. S. Bhave. S. Kulkarni , “Bond Graph Modelling of Single Stage Reciprocating air Compressor”, International Journal of Engineering Research & Technology (IJERT); ISSN: 2278-0181,Vol. 3 Issue 11, November-2014

2. Jose J. Granda, “The role of bond graph modeling and simulation in mechatronics systems An integrated software tool: CAMP-G, MATLAB–SIMULINK,” Elsevier Science Ltd. PII: S09 5 7-4 1 58 (0 2)0 00 2 9-6, 2002

3. T.K. Bera, A.K. Samantaray, R. Karmakar, “Bond graph modeling of planar prismatic joints,” Elsevier Ltd,doi:10.1016/j.mechmachtheory.2011.07.016, 2011.

4. Philippus J. Feenstra, Eric J. Manders, Pieter J. Mosterman, Gautam Biswas and Joel Kg/cm2nett, “Modeling and Instrumentation for Fault Detection and Isolation of a Cooling System,” Twente University,2002

5. HallvardEngja, Bond graph model of a reciprocating compressor. Journal of the Franklin Institute, 319(1/2):115–124, 1985.

6. B. Samanta and S. Devasia, “Modelling And Control Of Flexible Manipulators Using Distributed Actuators: A Bond Graph Approach,” IEEE Catalog Number 88TH0234-5,1988

7. R.M. Berger, H.A. EIMaraghy, “The Analysis of Simple Robots Using Bond Graphs,” Journal of manufacturing system volume 9/No. 1, 2003

8. Vjekoslav Damic, MajdaCohodar, “Bond Graph Based Modelling And Simulation Of Flexible Robotic Manipulators,” Proceedings 20th European Conference on Modelling and Simulation, 2006

9. P.M. Pathak, Amit Kumar, and N. Sukavanam**, “**Bond Graph Modeling of Planar Two Links Flexible Space Robot,” 13*th* National Conference on Mechanisms and Machines (NaCoMM07), IISc, Bangalore, India, December 12-13, 2007

10. G. Surya Kiran, Amit Kumar, Pushparaj M. Pathak, and N. Sukavanam, “Trajectory Control of Flexible Space Robot,” Proceedings of 2008 IEEE International Conference on Mechatronics and Automation, 2008

11. Rajkumar Jain , Pushparaj Mani Pathak, “Trajectory planning of 2 DOF planar space robot without attitude controller,” World Journal of Modelling and Simulation Vol. 4 (2008) No. 3, pp. 196-204 , 2008

12. MutukuMuvengei and John Kihiu, “Bond Graph Modeling of Mechanical Dynamics of an Excavator for Hydraulic System Analysis and Design,” World Academy of Science, Engineering and Technology, 2009

13. A. Mukhaerjee, R.Karmarkar,A.K.Samantaray, ”Bond Graph in Modeling, Simulaton and Fault identification,” I.K.International publishing House Pvt. Ltd., 2012

