Topological Simulaton of Dynamical Systems By Bond Graphs

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ABSTRACT

In this paper, a general topological method for the analysis and simulation of lumped-parameter dynamical systems is given. In order to model the problem, bond graph technique and THTSIM program language are used. Several examples are given for PDP-11 series of minicomputers.

ÖZET

Bu yazıda, toplu-parametreli dinamik sistemlerin analiz ve simülasyonu için genelleştirilmiş topolojik bir yöntem verilmiştir. Problemi modellemek için, bağlaç diyagramları tekniği ve THTSIM program dili kullanılmıştır. PDP-11 serisi minibilgisayarlar için birkaç örnek verilmiştir.

INTRODUCTION

The method of bond graphs is a most powerful technique of modern dynamical theory of control engineering today [1-4]. The significant advantage of this technique is being a direct method to obtain a mathematical model from a given multiport dynamical system. While there is still no a general topological method to find a unified model of these kind of systems. By the use of bond graph technique, all the energetic interactions can be modelled directly from the reticulation of system. This means that this approach is more general and practical with respect to classical topological system techniques. On the other hand, a bond graph is the representation that based on the concept of causality,

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so an operational model, such as block or signal - flow diagram representation can also be obtained from bond graph. This implies that an analog computer simulation can be done directly by bond graphing of a complex energy domain of system. However, analog computers are limited for the systems having large number of energy storage physical elements. While, digital computers have more capability of calculation and memories. By coding a bond graph ,a digital computer simulation can successefully be done. According to the concept of causality, different programs can be developed. Using bond graphs the first digital similaticn has been made by Rosenberg [5] by the language of ENPORT. This program is based on an acausal bond graph and it is useful for linear systems. In this program, a graph model of the system is accepted as iput data. The disadvantages of ENPORT are the restrictions to the linearity and requirement of a large computer. Also, the implementation has a time consumation. Although the other general languages, like CSMP, CSSL, MIMIC, MIDAS, etc. have been used but all of these languages require a mathematical model (preferably state-space modeling). ENPORT program or any other needs an extra work to obtain the response of the system.

It is known today that minicomputers have many advantages and give the opportunity of immediate contact of the system response. While by a large computer, a structure or parameteer change in the model may be taken hours. With minicomputers, it is also possible to stop the simulation and to change the parameters in any case. In minicomputers, the programs can be punched in papertapes or stored in cassettes or disks which give the opportunity to use them again immediately.

Using bond graphs a direct system simulation has been made firstly by THTSIM program by Kraan [6]. This language is a simulation program accepting a block diagram as input data. Later, van Dixhoorn [7] and Meerman [8] have developed THTSIM for PDP-11 series of minicomputers. The general characteristics of THTSIM are as follow,

(a). A block diagram or bond graph model is used as the input data, (b). Scaling is not necessary, (c). There are 40 about logic, algebraic and dynamic function blocks, (e). Simulation can be done in real time, (f). Analog input and output to external apparatus would be possible, (g). The model requires 4k 16-bit memory space for every 400 used function blocks, (h). The program is written in assembler and occupies 8k 16-bit words.

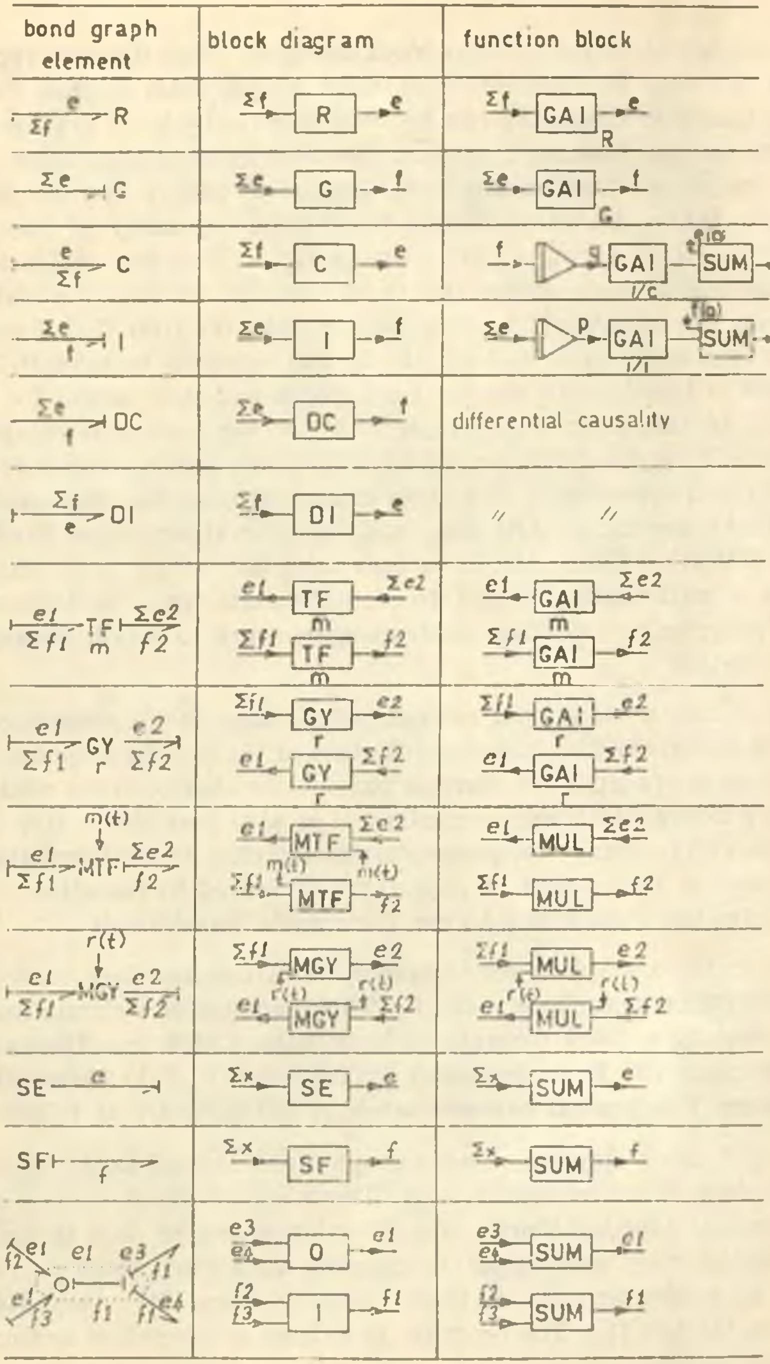


Fig. 1. Classification of all bond graph elements and their block diagram and operational equivalents.

Instead there are several minicomputer simulation languages which are useful for block diagram input formats. THTSIM is one of them but to accept a bond graph model as the input data.

2. SIMULATION BY THTSIM LANGUAGE USING BOND GRAPH INPUT DATA

Bond graphs are power-flow graphs and have all the physical flow and effort variables and their interactions and tranductions. They are easily convertable to block (or signal-flow) diagrams. An augmented bond graph (causal bond graph) is a complete representation of a dynamical system. The 0− and 1− junctions are the summation points (summer ampliffiers) and the causal strokes of bond graph elements show the computational operations. Already a bond graph element is equivalent to a simulation procedure (like a block diagram) and has an output according to its physical operation. In Fig. 1 all the bond graph elements and their block and functional equivalents are shown.

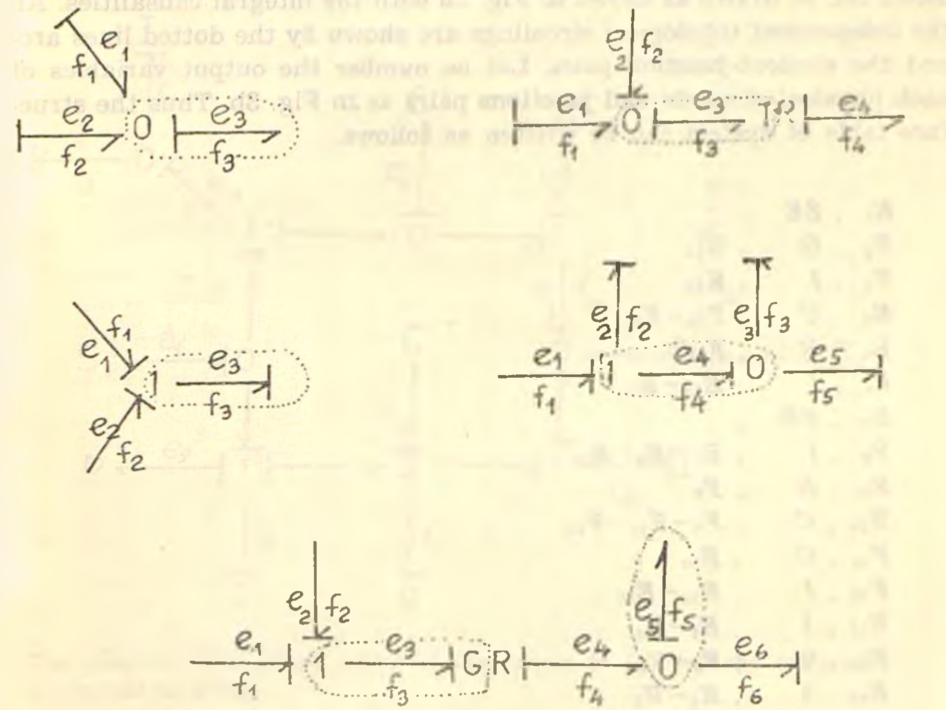


Fig. 2. Selections of possible independent topological encirclings of junction pairs.

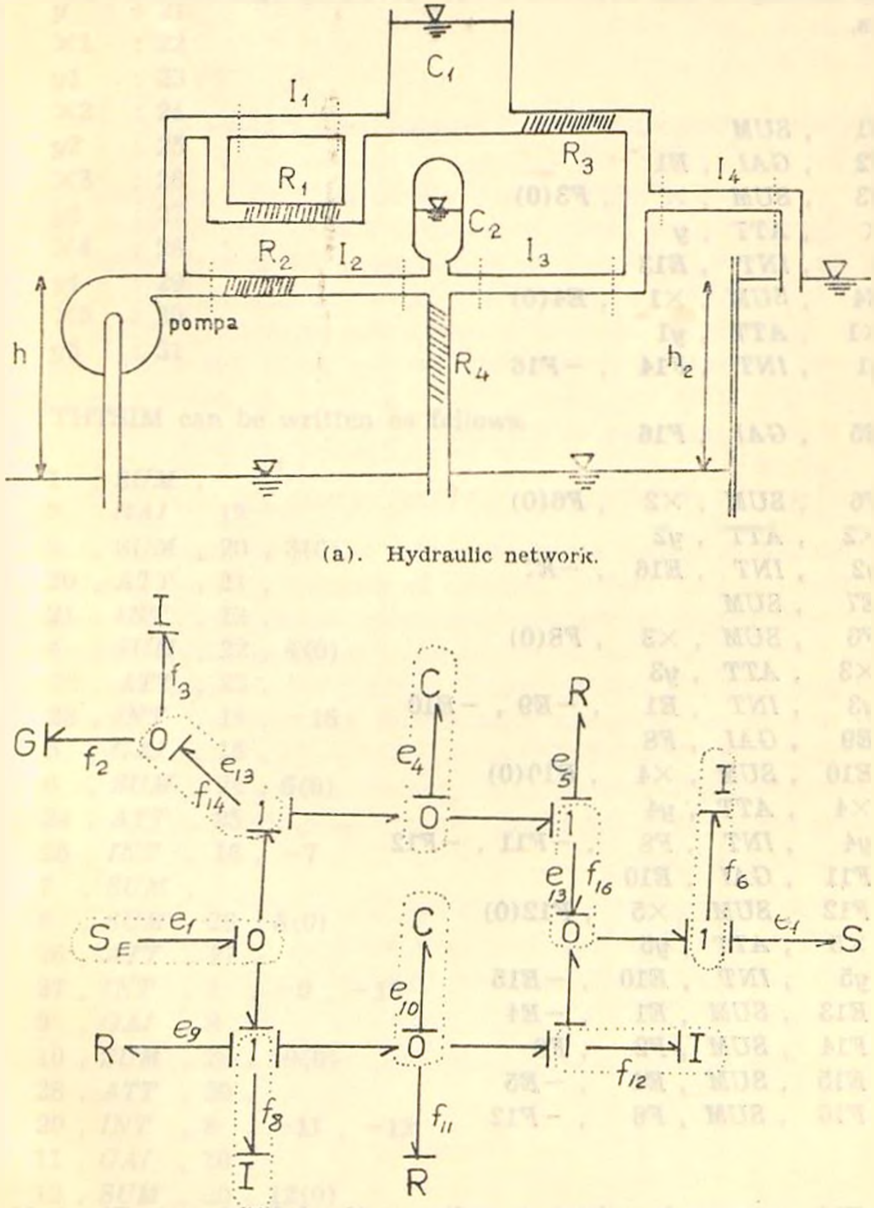
THTSIM program is based on a topological selection of the system variables of the bond graph elements which can be written directly from an augmented bond graph model of the system. Namely, THTSIM is a coding of the input-output variables of the bond graph components. This procedure is called as «structure table» which can be written as follows.

Output variables	physical components (one and multiports)	input variables
.	.	.
.	.	.
.	.	.

Output variables can be selected directly from the bond graph model. This selection has the minimum number of topological independent variables. These idependent variables are indicated by the encircled dotted lines around the junction pairs. These are summarized in Fig. 2. As we see, some of them have two different outputs and thus it is necessary to indicate by two numbers.

Example 1. In Fig. 3a a hydraulic network is shown. The bond graph model can be drawn as shown in Fig. 3b with the integral causalities. All the independent topological circulings are shown by the dotted lines around the element-junction pairs. Let us number the output variables of each physical elements and junctions pairs as in Fig. 3b. Thus the structure table of system can be written as follows.

E_1 ,	SE	
F_2 ,	G	, E_{13}
F_3 ,	I	, E_{13}
E_4 ,	C	, $F_{14}-F_{16}$
E_5 ,	R	, F_{16}
F_6 ,	I	, $E_{15}-E_7$
E_7 ,	SE	,
F_8 ,	I	, $E_1-E_9-E_{10}$
E_9 ,	R	, F_8
E_{10} ,	C	, $F_8-F_{11}-F_{12}$
F_{11} ,	G	, E_{10}
F_{12} ,	I	, $E_{10}-E_{15}$
E_{13} ,	1	, E_1-E_4
F_{14} ,	0	, F_2+F_3
E_{15} ,	1	, E_4-E_5
F_{16} ,	0	, F_6-F_{12}



(a). Hydraulic network.

(b). The complete bond graph model of the system in (a) and the independent topological encirlings.

Fig. 3. Modeling of a hydraulic network and its bond graph.

By looking to this structure table, THTSIM program can be done as follows,

```
E1  , SUM
F2  , GAI , E1
F3  , SUM , ×   , F3(0)
×   , ATT , y
y   , INT , E13
E4  , SUM , ×1  , E4(0)
×1  , ATT , y1
y1  , INT , F14 , −F16

E5  , GAI , F16

F6  , SUM , ×2  , F6(0)
×2  , ATT , y2
y2  , INT , E16 , −E7
E7  , SUM
F8  , SUM , ×3  , F8(0)
×3  , ATT , y3
y3  , INT , E1  , −E9 , −E10
E9  , GAI , F8
E10 , SUM , ×4  , E10(0)
×4  , ATT , y4
y4  , INT , F8  , −F11 , −F12
F11 , GAI , E10
F12 , SUM , ×5  , F12(0)
×5  , ATT , y5
y5  , INT , E10 , −E15
E13 , SUM , E1  , −E4
F14 , SUM , F2  , F3
E15 , SUM , E4  , −E5
F16 , SUM , F6  , −F12
```

This program is written according to the definitions in Fig. 1. Now numbering the variables once again we can write this listing. This listing is the program of THTSIM and can be loaded on the computer. This new list is exactly the same as THTS1M. Let us define first the coordinates.

```
×    : 20
y    : 21
×1   : 22
y1   : 23
×2   : 24
y2   : 25
×3   : 26
y3   : 27
×4   : 28
y4   : 29
×5   : 30
y5   : 31
```

THTSIM can be written as follows.

```
1  , SUM ,
2  , GAI , 13
3  , SUM , 20 , 3(0)
20 , ATT , 21 ,
21 , INT , 13 ,
4  , SUM , 22 , 4(0)
22 , ATT , 23 ,
23 , INT , 14 , −16
5  , GAI , 16 ,
6  , SUM , 24 , 6(0)
24 , ATT , 25 ,
25 , INT , 16 , −7
7  , SUM ,
8  , SUM , 26 , 8(0)
26 , ATT , 27 ,
27 , INT , 1  , −9 , −10
9  , GAI , 8 ,
10 , SUM , 28 , 10(0)
28 , ATT , 29 ,
29 , INT , 8  , −11 , −12
11 , GAI , 10 ,
12 , SUM , 30 , 12(0)
30 , ATT , 31 ,
31 , INT , 10 , −15
13 , SUM , 1  , −4
```

14 , *SUM* , 2 , 3
15 , *SUM* , 4 , −5
16 , *SUM* , 6 , −12

3. ANALOG PROGRAMMING USING THTSIM LANGUAGE

In fact the above implementation is an analog programming. This list of programming can easiliy be set up by a block diagram as shown in Fig. 4. As we see, it is possible to simulate the system by THTSIM language for both digital and analog programming. Although the application of the technique has been shown in this paper for PDP - 11 series of minicomputers, bond graphs may also be useful for other type of computers. For IBM computers, CSMP program is more convenient [9] but it is not as quick as THTSIM.

4. SIMULATION OF SYSTEMS HAVING COMPLEX MOTIONS

A dynamical system containing parts having simultanous motions both translation and rotation that can be depicted by bond graphs succesfully with respect to classical topological techniques. Linear graph notation becomes cumborsome when applied to systems involving energy transductions. In this case a separete linear graph is required for each energy domain and energetic relationships are obscured. Whereas, to show these energy trusductions twoport bond graph elements even considering control coefficients (in bond graph terminology, these are called as «active bonds» [2] (. Let us take the system in Fig. 5 that has a coplex mechanical motions.

For the motions of the sistem in Fig. 5, a coordinate transformation must be definer between two coordinate systems, (X, y) and (r, θ). By the vector and bond graph notatoins this transformation can be shown as in Fig. 6.

From Fig. 6a this transformation, one can write the following relationships,

$$X = r\cos\theta \qquad (1)$$
$$y = r\sin\theta$$

where, X, y and r are the translational and θ is the rotational coordinates. And the velocities can be written as

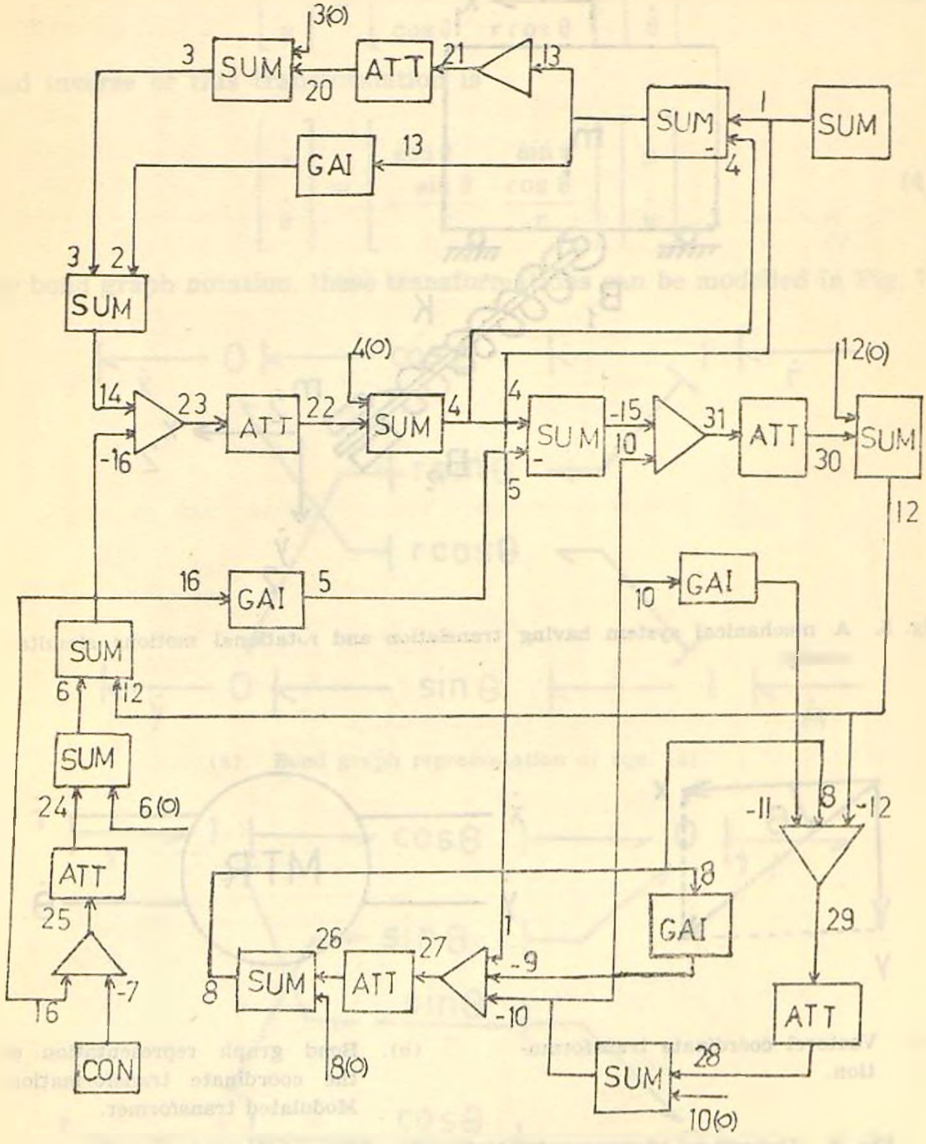


Fig. 4. Analog simulation by THTSIM language.

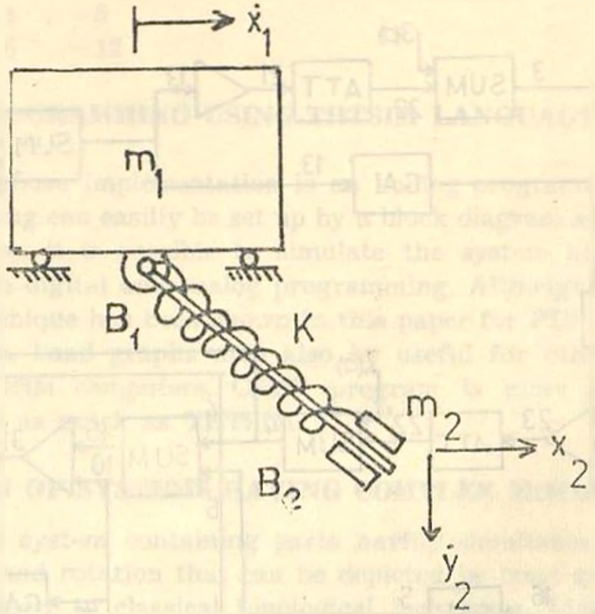
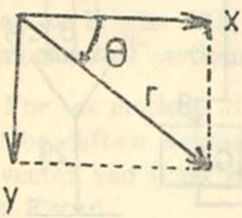


Fig. 5. A mechanical system having translation and rotational motions simultanously.



(a). Vectorel coordinate transformation.

(b). Bond graph representation of the coordinate transformation: Modulated transformer.

Fig. 6. Definitions of the coordinate transformation of the motion in Fig. 5.

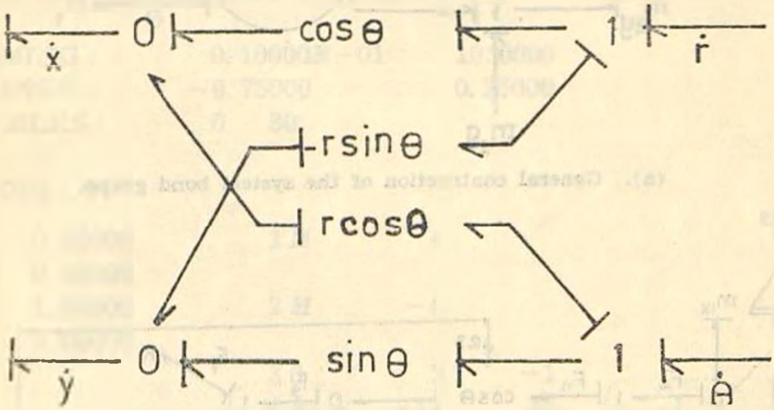
$$\dot{x} = \dot{r}\cos\theta - r\sin\theta\cdot\dot{\theta}$$
$$\dot{y} = \dot{r}\cos\theta + r\cos\theta\cdot\dot{\theta} \qquad (2)$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \cos\theta & -r\sin\theta \\ \cos\theta & r\cos\theta \end{bmatrix} \begin{bmatrix} \dot{r} \\ \dot{\theta} \end{bmatrix} \tag{3}$$

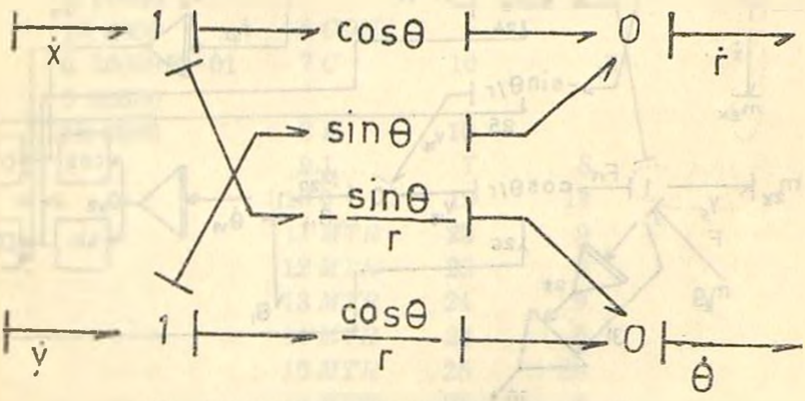
and inverse of this transformation is

$$\begin{bmatrix} \dot{r} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\dfrac{\sin\theta}{r} & \dfrac{\cos\theta}{r} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} \tag{4}$$

By bond graph notation, these transformations can be modelled in Fig. 7

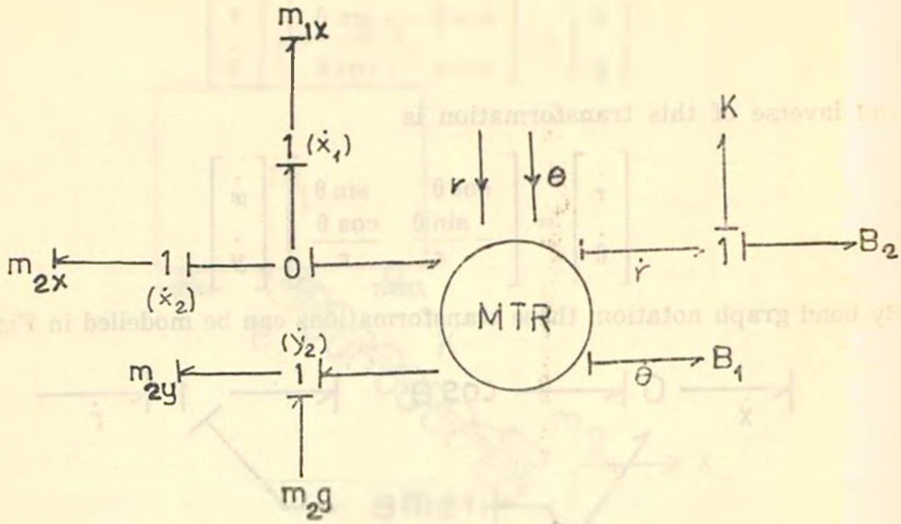


(a). Bond graph representation of eqn. (3)

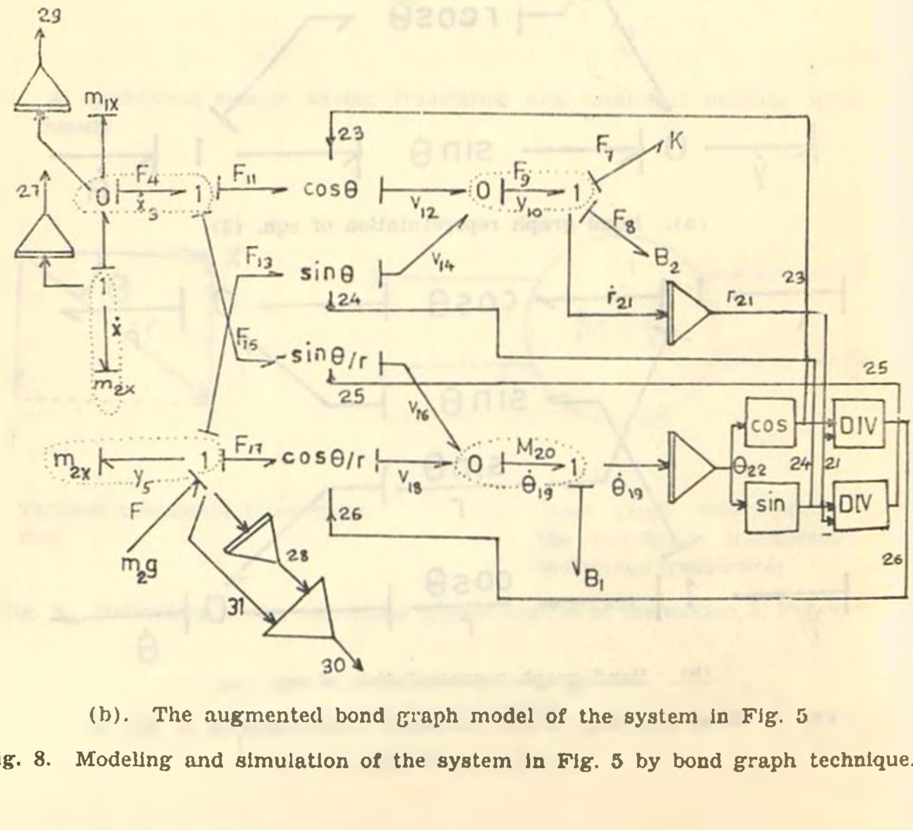


(b). Bond graph representation of eqn. (4)

Fig. 7. Bond modeling of the coordinate transformation in Fig. 6.



(a). General contruction of the system bond grapn.



(b). The augmented bond graph model of the system in Fig. 5

Fig. 8. Modeling and simulation of the system in Fig. 5 by bond graph technique.

Thus, a complete bond graph model of the system can be drawn as shown in Fig. 8

In principle, the system bond graph can be constructed as shown in Fig. 8a. The complete (augmented) bond graph is drawn with all the causality assignement. As we see, the causality assignements satisfy the concept of state variables. The topological selection of the system variables are numbered refering the encirclings. The signals 23, 24, 25 and 26 are the active bonds (control coefficients). By looking the augmented bond graph in Fig. 8b directly a structure table can easily be written that leads to the following THTSIM program.

```
TIMING :          0.10000E-01      10.0000
RANGE :          -0.75000          0.25000
PLBLKS :          0    30

MODEL :

    0.50000           1 M         4
    0.00000
    1.00000           2 M        -4
    0.00000
                      3 0         2        -1
                      4 1        11        15
    1.00000           5 M       -13       -17      6
    0.00000
    10.0000           6 CON
    0.10000E-01       7 C        10
    0.00000
    10.0000           8 R        10
                      9 1         7         8
                     10 0        12        14
                     11 MTR      23         9
                     12 MTR      23         3
                     13 MTR      24         9
                     14 MTR      24         5
                     15 MTR      25        20
                     16 MTR      25         3
                     17 MTR      26        20
                     18 MTR      26         5
                     19 0        16        18
```

0. 10000E−01	20 *R*	19	
0. 25000	21 *INT*	10	
0. 00000	22 *INT*	19	
	23 *COS*	22	
	24 *SIN*	22	
	25 *DIV*	24	−21
	26 *DIV*	23	21
0. 25000	27 *INT*	2	
0. 00000	28 *INT*	5	
−0. 25000	29 *INT*	1	
	30 *SUN*	−23	31
−0. 25000	31 *CON*		

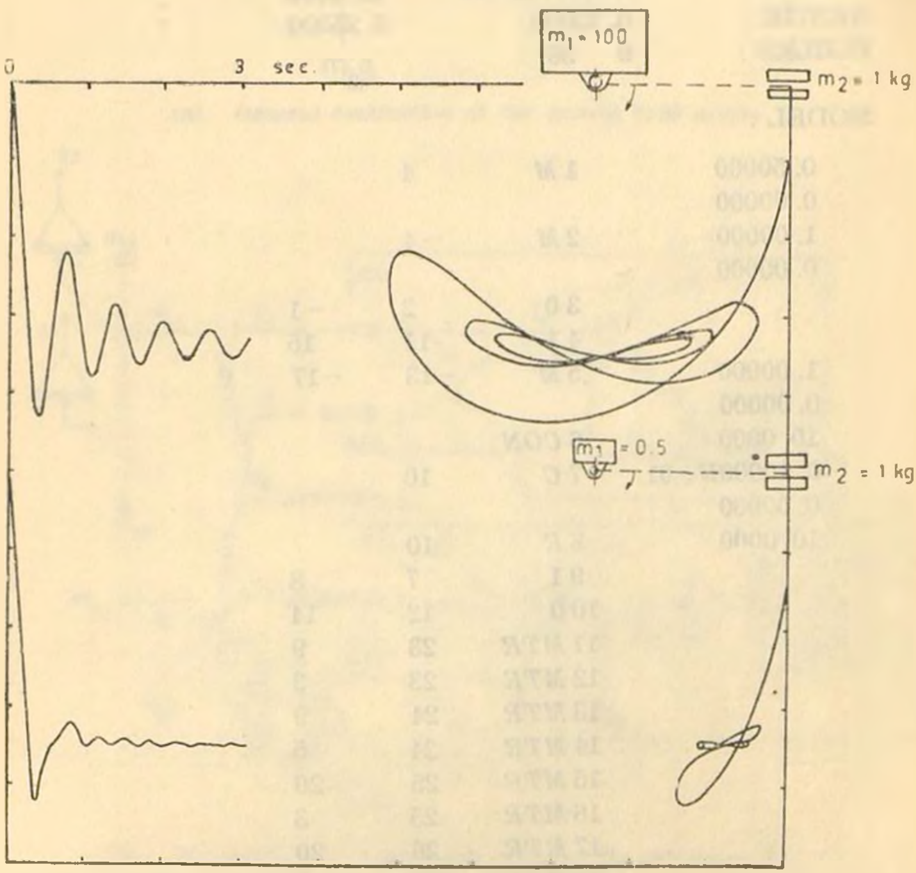


Fig. 9. The simulation responses or the x - y and y - t plotters.

(The above listing of THTSIM has made in Twente Technological University, Electrical Engineering Department, Enschede, Holland in October 20, 1977 on PDP-11/20 minicomputer).

Fig. 9 shows the system response that has been obtained from the plotter of computer. As we see, two responses have been found, first for the mases, $m_1=100$ kg, $m_2=1$ kg and $m_1=0{,}5$ kg, $m_2=1$ kg.

5. CONCLUSION

In this paper it has been shown that how a dynamical system can be simulated on a minicomputer to accept the bond graph model of the system as the input data. In order to show the approach a special simulation language, called THTSIM has been used. As they are seen from the examples, THTSIM is more practical and easier with respect to the other block or bond graph oriented languages and does not need to write first any mathematical formulation. However if it is requested a mathematical model this may be easily found. Because already the structure table of a bond graph is a listing model of any mathematical (for instance state-space) model. This particular problem however has not been considered here.

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