MODELING AND SIMULATION OF ADAPTIVE VEHICLE AIR SUSPENSIONS WITH PSEUDO BOND GRPAHS, CAMP AND ACSL

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Abstract

Air suspensions involve interactions among mechanical, pneumatic, electrical and hydraulic elements. Pseudo bond graphs, true bond graphs and block diagrams can be used to model electronically controlled suspensions in a convenient and concise way. The CAMP program produces the equations of motion in the form of an input file for a general purpose simulation program such as ACSL. After editing of the file to insert nonlinear constitutive laws and control system equations, simulation of the system can be accomplished in the usual way. Using macros or sub-routines, commonly occurring elements such as pneumatic accumulations and restrictors can be conveniently represented.

I. Introduction

Air suspensions have long been in use for automobiles, trucks and busses but interest in such suspensions has increased recently with the production of electronically controlled systems. The ride height of the vehicle can be adjusted for load leveling or aerodynamic drag reduction and the effective volume of air can be varied to change the stiffness of the suspension.

Figure 1 shows a highly schematic sketch in which a 2 degree-of-freedom model represents one-quarter of an automobile. The body is represented by the mass M the wheel by m and the tire by the spring with constant k. The air suspension itself is shown as a rolling diaphragm with effective area A and variable volume V_1. When the valve with area A_{12} is open, the volume V_2 supplements V_1. The volumes V_2 and V_3 are supposed to be continuously variable as the piston with area A' is moved back and forth by an electric drive system. (The drive must be self-locking so that pressure differences across the piston do not cause movement.) The area A_{23} represents a leakage path between V_2 and V_3 which provides a long-term pressure equilization. Present day switched stiffness suspensions can be modeled by opening and shutting the area A_{12} and continuously variable sysems are modeled by considering movement of the piston separating the volumes V_2 and V_3. Ride height control is achieved by activating the valve on the left side. Area A_{1a} allows air to escape to the atmosphere and A_{1s} allows air from a supply vessel to enter the volume V_1. The valve actuator varies A_{1a} and A_{1s} simultaneously. The damper between the wheel and the body would typically be a hydraulic shock absorber with electro-mechanical valves to vary the damping properties of the device.

II. Basic Pneumatic Systems Elements

The construction of a bond graph representation for the mechanical, electromechanical or hydraulic parts of a system such as that in Fig. 1 is routine, [1]. Compressible fluid systems and thermal systems modeled using a control volume approach can be conveniently incorporated in a pseudo bond graph, [2-7]. In such a bond graph, effort and flow variables are used which are not complementary power variables. Except for this, however, the sign convention and causality operations as well as the basic classifications of R and C elements are the same as in the case of true bond graphs.

We consider now specific models for the two pneumatic elements which appear in systems such as that in Fig. 1. The first called an accumulator as shown in Fig. 2. A mass M of gas is contained in a variable volume V with energy E, pressure P and temperature T. We consider P and T to be efforts and $\dot{E}$, $\dot{M}$, and $\dot{V}$, to be flows. The bond with P and $\dot{V}$ is a true bond since $P\dot{V}$ is power expended during a volume change. However, the paired bonds with T and $\dot{E}$ and P and $\dot{M}$ are pseudo bonds. The "thermal bonds" with T and $\dot{E}$ variables are shown dotted merely for convenience to distinguish them from their P, $\dot{M}$. partners. The use of C for the 3-port implies that the efforts P, P, and T should be functions of the displacements E, M, and V which are the time integrals of the flows.

If we assume, as is common [8,9] that the ideal gas laws are sufficiently accurate

$$PV = MRT \quad , \tag{1}$$

$$E = Mc_vT \quad , \tag{2}$$

where R is the gas constant and c_v is the specific heat at constant volume, then the accumulator in integral causality has the contitutive laws

$$P = (R/c_v)E/V \quad , \tag{1'}$$

$$T = (1/c_v)E/M \quad , \tag{2'}$$

(Equation (1') yields the effort for two of the C's bonds.) The initial values of the state variables V_0, M_0, E_0 are related to initial pressure and temperature by

$$M_0 = P_0V_0/R\ T_0 \quad , \tag{3}$$

$$E_0 = P_0V_0c_v/R \quad , \tag{4}$$

The two zero junctions in Fig. 2 are used to enforce conservation of mass and energy as air flows into and out of the accumulator. The extra flow source is necessary to assure that the mechanical power $P\dot{V}$ is properly considered in the rate of change of energy stored in the gas. Other energy flow rates come from heat transfer or enthalpy flows of the form $\dot{m}c_pT$ where $\dot{m}$ is a mass flow rate, c_p is the specific heat at constant pressure and T is the gas temperature.

Figure 3 shows a psuedo bond graph for another common element in pneumatic systems. It is called a restrictor and it represents valves if the area A is variable or a fixed orifice if A is constant. Here we will use a model based on isentropic nozzle equations, [8,9], which will consider forward and reverse flow and choking.

We assume that the pressures P_a, P_b and temperatures T_a, T_b, on the two sides of the restrictor are inputs and the mass flow rate $\dot{m}_a$, $\dot{m}_b$ and energy flow rates $\dot{E}_a$, $\dot{E}_b$ are to be calculated. The procedure is as follows:

1. Decide on upstream and downstream variables.

$$\text{If } P_a > P_b \text{ , } P_u = P_a \text{ , } T_u = T_a \text{ , } P_d = P_b \text{ ,}$$

$$\text{If } P_b \leq P_a \text{ , } P_u = P_b \text{ , } T_u = T_b \text{ , } P_d = P_a \qquad (5)$$

2. Compare the pressure ratio to the critical pressure ratio, P_{cr}

$$P_{cr} = [2/(\gamma-1)]^{[\gamma/(\gamma-1)]} \text{ ,} \qquad (6)$$

where $\gamma = c_p/c_v$. (7)

$$\text{If } P_d/P_u > P_{cr} \text{ , } P_r = P_d/P_u \text{ ,}$$

$$\text{If } P_d/P_u \leq P_{er} \text{ , } P_r = P_{cr} \text{ .} \qquad (8)$$

3. Compute a mass flow rate.

$$in = \frac{A\ C_d P_u}{\sqrt{T_u}} \sqrt{\frac{2\gamma}{R(\gamma-1)}} \sqrt{P_r^{2/\gamma} - P_r^{(\gamma-1)/\gamma}}$$

where C_d is a discharge coefficient.

4. Correct for direction of flow.

$$\text{If } P_a > P_b \text{ , } \dot{m}_a = \dot{m}_b = \dot{m}$$

$$\text{If } P_a \leq P_b \text{, } \dot{m}_a = \dot{m}_b = -\dot{m} \qquad (10)$$

5. Compute energy flow rate.

$$\dot{E}_a = \dot{E}_b = \dot{m}_a\ c_p\ T_u \qquad (11)$$

Note that it is possible to define a different discharge coefficient for forward and reverse flows in step 1.

With specific constitutive laws for accumulators and restrictors, it is possible to assemble a bond graph model for the suspension of Fig. 1 as well as a variety of other pneumatic systems.

III. Automatic Equation Formulation

An advantage of bond graphs lies in their compact nature. Figure 4, for example, represents the system of Fig. 1 in a much more precise way than the schematic diagram and yet it shows clearly the types of elements and their connection laws. The left side of the figure represents the mechanical dynamics with true bond graph elements. The MTF at the lower left converts forward velocity into vertical input velocity to the tire through the roadway unevenness slope function which depends on the position variable X. On the right side, there are three accumulators for the three volumns and four restrictors for the valves and leakage passages. Physical parameters and variables are indicated on this bond graph to aid in relating it to the schematic diagram. Also, a number of signal interactions are shown with full arrows as signals or activated bonds. The valve areas and the variable damper are to be varied by the electronic control system. Other signals arise because the pseudo bond graph interacts with a true bond graph.

Another version of the system bond graph showing and numbering all bonds but suppressing control system signals is shown in Fig. 5. This bond graph shows the basic energetic structure of the physical system and the equations of motion for this system. For nonlinear systems, it is convenient to write out the constitutive laws in causal form for each multiport element without elimination of internal variables, [10].

The analysis of causal interactions among multiport elements follows a strict procedure, [1]. In the CAMP program, [11] this process has been automated. CAMP functions as a preprocessor for a variety of continuous system simulators such as ACSL [12].

The input to CAMP is a line code as shown in Fig.6. It is a listing of the multiport type followed by the numbers of all attached bonds. The sign convention half arrow is assumed to point from the first listed multiport to the later listed multiport for any bond number. (When there are loops in bond graph junction structures, one may occasionally have to insert 2-port 0- or 1-junctions in order to achieve an ordering equivalent to a given set of sign convention half-arrows.) There are several projects to develop means to draw bond graphs on a graphics terminal and to generate the line code for CAMP automatically [13].

CAMP analyses the line code to make sure that it is complete and then checks for derivative causality and algebraic loops. If no problems occur, the causal equations for each multiport are written as if the multiport were linear and incorporated in an input file for the simulator program. For the multiports, which are actually linear, coefficient values must be supplied while for nonlinear multiports the linear relations are replaced by nonlinear ones in an editing process.

IV. Completion of the System Model

The result of a CAMP run on the line code of Fig. 6 is an input file for ACSL consisting of a large number of simple, linear, causal equations. In the example, CAMP writes about 125 equations, many of which are trivial identities and sums from the junction structure while the physical system is only 13th order.

Figure 7 shows a small portion of the CAMP generated ACSL input file. Note the 4-port R relations for a restrictor, part of the 3-port C relations for an accumulator, some derivative definitions, some junction structure laws and some state variable integration definitions in the ACSL format.

In Fig. 8, an ACSL macro is shown for the accumulator, Eqs. (1') and (2'), and for the restrictor or valve, Eqs. (5) to (11). Figure 9 shows how the two macros are used as functions to replace the 4-port R and 3-port C linear relations of Fig. 7 with nonlinear versions.

The remainder of the system model is written using the ACSL language in a standard fashion. For the suspension example, one needs to develop a control algorithm for stroking the values and varying the volumes and one needs to decide on test inputs from the roadway unevenness or from external forces in order to exercise the model. It is often useful to construct a block diagram for candidate control systems particularly if nonlinear functions are to be incorporated.

V. Conclusions

The use of bond graph models, an equation formulator such as CAMP and a general purpose simulator such as ACSL in combination has resulted in increased productivity in modeling, analysis, and simulation of dynamic systems containing physical elements. Work of a routine nature such as writing equations for a rigorously defined model is aided to the maximum extent possible by the computer. The bond graph model and the power flow sign conventions implied by the line code order are documented in the CAMP output automatically so the results of previous simulations can be easily checked. The use of bond graph methods for the study of systems such as electronically controlled suspensions in which a variety of energy domains are involved and in which nonlinearities are of crucial importance has proved useful.

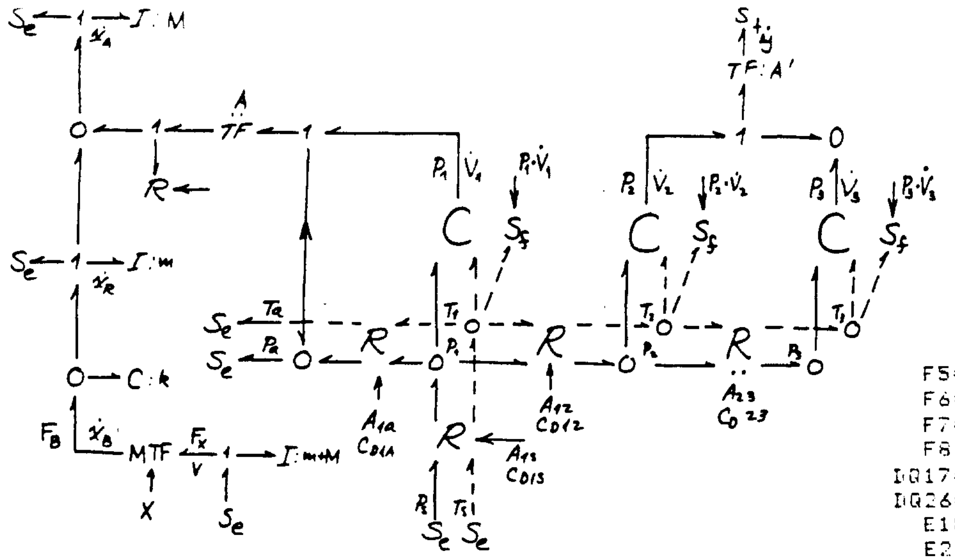

Figure 4 Bond Graph with Physical Variables Corresponding to Fig. 1

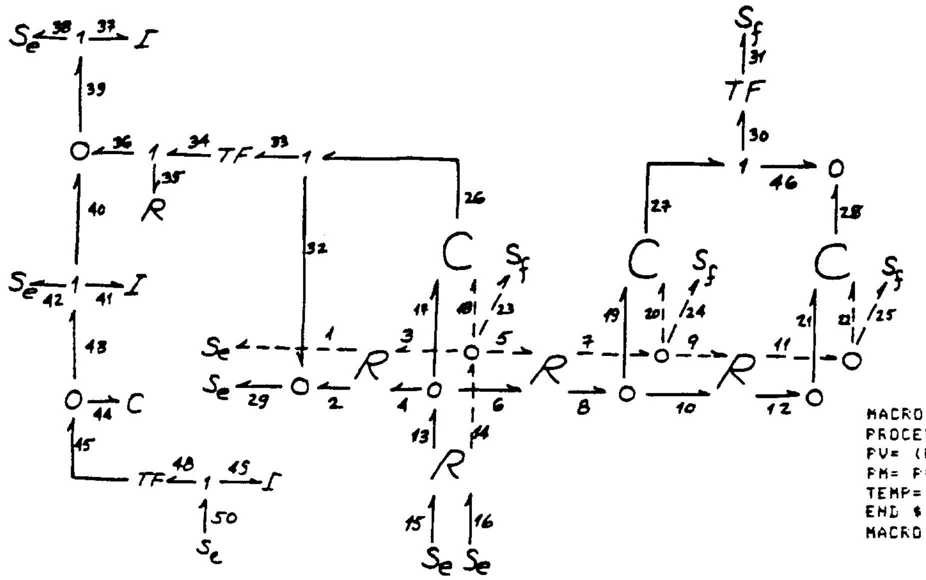

Figure 5 Bond Graph with Numbered Bonds

```
SE50, 1 48 49 50, I49, TF48 45,
SE15, SE16, R13 14 15 16,
0 13 6 4 17, 0 14 18 23 3 5, R1 2 3 4,
R5 6 7 8, C17 18 26, 0 8 10 19,
0 7 20 24 9, R9 10 11 12, 0 12 21,
0 11 22 25, C19 20 27, C21 22 28,
1 32 26 33, 0 29 32 2, TF34 33, 1 34 35 36,
0 43 44 45, 1 40 41 42 43, 0 39 36 40,
1 37 38 39, 1 27 30 46, 0 46 28, TF30 31,
SE38, I37, SE42, I41, C44, R35, SE1,
SE29, SF23, SF24, SF25, SF31
```

Figure 6 Line Code Input for CAMP Corresponding to the Bond Graph of Fig. 6

```
  F5=E5*R55+E6*R56+E7*R57+E8*R58
  F6=E5*R65+E6*R66+E7*R67+E8*R68
  F7=E5*R75+E6*R76+E7*R77+E8*R78
  F8=E5*R85+E6*R86+E7*R87+E8*R88
DQ17=F17                          $
DQ26=F26                          $
  E18=Q17/C1817+Q18/C1818+Q26/C1826
  E26=Q17/C2617+Q18/C2618+Q26/C2626
  F19=F8-F10                      $
  E10=E19                         $
  E7=E20                          $
  E9=E20                          $
'...... STATE VARIABLES ......'
   P49= INTEG (DP49,P49IN)
   Q17= INTEG (DQ17,Q17IN)
   Q18= INTEG (DQ18,Q18IN)
   Q26= INTEG (DQ26,Q26IN)
```

Figure 7 Portion of CAMP Ouput

```
MACRO ACCUM (PV,PM,TEMP,VOL,MASS,ENGY)
PROCEDURAL (PV,PM,TEMP=VOL,MASS,ENGY)
PV= (R/CV)*(ENGY/VOL)
PM= PV
TEMP= (1./CV)*(ENGY/MASS)
END $'OF PROCEDURAL'
MACRO END

MACRO VALVE(MA,MB,EA,EB,PA,PB,TA,TB,A,CD)
PROCEDURAL (MA,MB,EA,EB=PA,PB,TA,TB,A,CD)
PU=PB
PD=PA
TU=TB
IF(PA .GT. PB) PU=PA
IF(PA .GT. PB) PD=PB
IF(PA .GT. PB) TU=TA
PR=PD/PU
IF(PR .LE. PCR) PR=PCR
MDOT=A*CD*(PU/SQRT(TU))*SQRT(2.0*GA/(R*(GA-1.0))) ...
*SQRT(PR**(2.0/GA)-PR**((GA+1.0)/GA))
MA=MDOT
IF(PB .GE. PA) MA=-MDOT
MB=MA
EA=MA*CP*TU
EB=EA
END $'OF PROCEDURAL'
MACRO END
```

Figure 8 Accumulator and Restrictor Macros

```
 VALVE(F4,F2,F3,F1=E4,E2,E3,E1,A1A,CD1A)
 VALVE(F6,F8,F5,F7=E6,E8,E5,E7,A12,CD12)

DQ17=F17                         $ DQ18=F18
DQ26=F26

 ACCUM(E26,E17,E18=Q26,Q17,Q18)
```

Figure 9 Portion of Edited ACSL Input File

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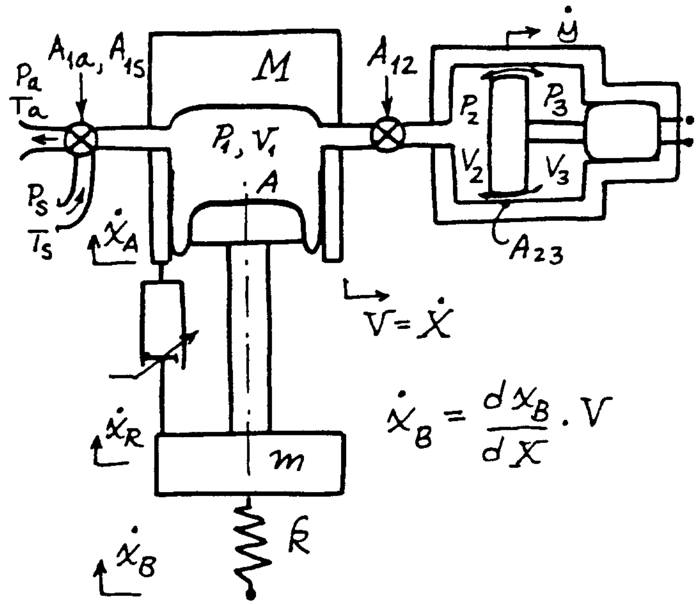

Figure 1 Schematic Diagram of Air Suspension Unit

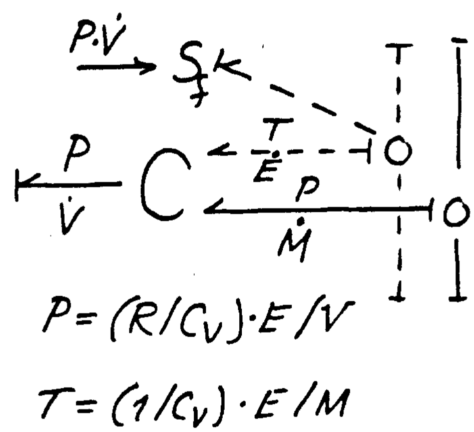

Figure 2 Ideal Gas Accumulator

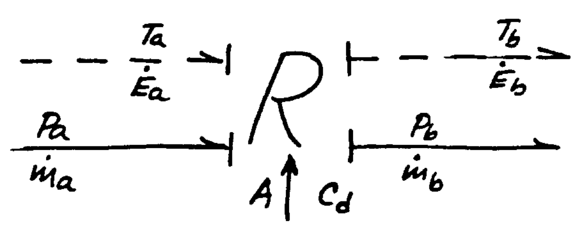

Figure 3 Pseudo Bond Graph for Restrictor