15th Triennial World Congress, Barcelona, Spain

PASSIFICATION OF ELECTROHYDRAULIC VALVES USING BOND GRAPHS

Perry Y. Li [*,1] **Roger F. Ngwompo** [**,2]

[*] *Department of Mechanical Engineering,*
University of Minnesota,
111 Church St. SE,
Minneapolis, MN 55455,
U.S.A.
[**] *Department of Mechanical Engineering,*
University of Bath,
BATH BA2 7AY,
United Kingdom.

Abstract: In many applications that require physical interaction with humans or other physical environments, passivity is a useful property to have in order to improve safety and ease of use. Many hydraulic applications (e.g. a human operated excavator) fall into this category. In a previous work, the passivity property of a directional hydraulic flow control valve, and methods for making the valve in a passive two-port system were proposed. In this paper, the problem of developing passifying control laws for directional control valves is re-visited from a bond graph perspective. Two new bond graph elements with power scaling properties are first introduced and the passivity property of bondgraphs containing these elements are investigated. Then by representing the control valve in a suitable augmented bond graph, and by replacing the signal bonds with power scaling elements, it is shown that passifying control laws can easily be recovered and generalized.

Keywords: Passivity, bond graphs, power transformer, control valves, electro-hydraulics

1. INTRODUCTION

In the operation of systems requiring contacts with the environment or direct control by humans, passivity is an important property as it is related to both the safety and the ease to control the overall system. A passive system can be briefly described as a system that does not generate energy but only stores, dissipates, and releases it. The amount of energy that a passive system can impart to the environment is limited by the external input and so some safety is ensured compared to non-passive systems (Colgate 1994). It also appears that because of the ability to use the concept of “power" to plan and execute manipulation tasks, passive systems are also potentially easier to use.

From the above observations, it would be helpful to use passive systems in tasks that require contacting the physical environment and/or direct control by humans. The passivity property of electro-mechanical systems is well known and have been exploited to develop overall control systems that are closed loop passive (see for example (Li and Horowitz 1997). Although many hydraulic systems (e.g. in construction equipment) involve direct human operation, and direct contact, the passivity concept has not been applied to electro-hydraulic control systems until recently (Li 2000). In (Li 2000), the passivity property of the

[1] Email: pli@me.umn.edu. Partially supported by the National Science Foundation grant ENG/CMS-0088964.
[2] Email:ensrfn@bath.ac.uk

directional control valve was investigated from the controls perspective, and the valve was shown to be non-passive. Two alternative methods were proposed to make this device passive: by making structural or hardware redesign or by implementing active feedback compensation. Subsequently, the actively feedback compensated passified valve was used to develop a passive bilateral teleoperation scheme for electrohydraulic actuators (Li and Krishnaswamy 2001).

Bond graph is a physical approach to the modeling of physical systems that have increasingly been used in the analysis of systems for design and control ((Ngwompo and Gawthrop 1999, Huang and Youcef-Toumi 1999). The inherent concept of power and energy embedded in bond graph representations suggests that this tool can be used to investigate the passivity property of systems and possibly provide alternative or generalized methods to make a system passive. The objective of this paper is then to revisit the passivity and passification of the hydraulic valve using bond graph techniques. From the full understanding of this example, a general procedure can be proposed to make a non-passive system passive. This paper is organized as follows. In section 2, the definition of passivity, its relationship to regular bond graphs, and a brief problem statement are given. In section 3, two new bond graph elements are introduced. Bond graph models of a directional control valve are presented in Section 4. The passification algorithm for the valve, developed using the bond graph perspective is given in Section 5. Some remarks regarding the generalization of the proposed bond graph is given in Section 6. Section 7 contains some concluding remarks.

2. PASSIVITY AND BOND GRAPH

Given a dynamic system with input u and output y, a supply rate for the system can be defined to be any function $s(u,y) \in \Re$ which, considered a function of time, is L_1 integrable for any finite time ($\in L_{1e}$). A system is said to be passive with respect to this supply rate $s(u,y)$ if, for any given initial condition, there exists a constant so that for all time and for all inputs,

$$\int_0^t s(u(\tau),y(\tau))d\tau \geq -c^2. \qquad (1)$$

Assume that the input u and output y are colocated effort and flow variables for a physical system, then a physically meaningful supply rate can be defined to be the inner product between the input and the output. This supply rate (with proper sign conventions) represents the power input into the system. In this case, the passivity condition (1) expresses the fact that for all input $u(\cdot)$ and the corresponding output $y(\cdot)$, no matter how the input is manipulated and how much time one waits, the maximum amount of energy that can be extracted from the system is limited by the constant c^2 (depends on initial conditions but not on time interval or inputs), which can be interpreted as the initial energy stored in the system.

A standard regular bond graph consists of interconnections of dissipative (R-), capacitive (C-) and inertance (I-) elements, transformers and gyrators, and their multi-port generalizations. These components are either energy conserving or dissipative. Interconnections are made through "power bonds"or the "0-" (common effort) or "1-" (common flow) junctions via the colocated effort variables, ensuring power continuity. These standard components and connections are suitable for physical systems. In more modern development, signal bonds in which power continuity is not guaranteed are also introduced in order to represent a wider class of mechatronic / control systems. Later in this paper, we shall introduce new elements that have power scaling properties between its ports.

Lemma 1. Consider a regular bond graph with no active bonds or power scaling components. With respect to input bonds $i_1, i_2, \ldots, i_k$ (assuming all the sign conventions of all input bonds correspond to power input into the system when the variables are positive) with effort and flow variables e_{i_j}, f_{i_j}, $j = 1, \ldots, k$, the system is passive respect to the supply rate:

$$s(f_{i_1}, \ldots, f_{i_k}, e_{i_1}, \ldots, e_{i_k}) := \sum_{j=1}^{k} f_{i_j} e_{i_j}. \qquad (2)$$

In order words, given a set of initial conditions, there exists $c \in \Re$ s.t. for any inputs, and for any time $t \geq 0$,

$$\int_0^t s(f_{i_1}(\tau), \ldots, f_{i_k}(\tau), e_{i_1}(\tau), \ldots, e_{i_k}(\tau))d\tau \geq -c^2.$$

PROOF. Let the storage function W be the sum of the energies in the storage elements. Using the constitutive relationship of each element and the continuity of power in the junction structure, it is easy to show that

$$\dot{W} \leq \sum_{j=1}^{k} f_{i_j} e_{i_j}.$$

Integrating, and using the fact that $W(t) \geq 0$, we obtain

$$-W(0) \leq W(t) - W(t=0) \leq \int_0^t \left[\sum_{j=1}^{k} f_{i_j} e_{i_j} \right] d\tau.$$

□

Therefore, a system that can be modeled by a regular bond graph (such as a physical system) is passive if all its ideal effort and flow sources (S_e or S_f) are considered outside the system, and the supply rate defined to be the total power input from these sources. In many control systems, however, the power source is unmodulated and is part of the system. The controller performs the conversion of this power from the sources. Therefore, a more meaningful way of looking at passivity would be in terms of the interactions of the system (including the power sources) with the controller (the algorithm), and with the external environment. The questions we are addressing in the subsequent sections are:

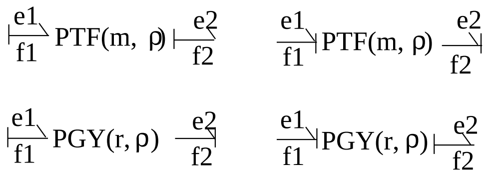

Fig. 1. Causal relations of power scaling transformers / gyrators.

a) how to appropriately represent this power modulation using bond graphs so that the passivity property of the control system can be investigated.
b) how to determine a controller that makes the control system passive and how to represent the "equivalent" passive control system with bond graphs.

3. POWER SCALING TRANSFORMERS / GYRATORS

Before proceeding, we introduce two new bond graph elements: *power scaling transformers* and *power scaling gyrators*. The causal properties of these elements follow the regular two-port transformers and gyrators. The difference is that there is a possibly non-unity scaling factor that relates the power inputs at the two ports. Specifically, $PTF(m,\rho)$ denotes a power scaling transformer with transformer modulus m and power scaling ρ in Fig. 1. Its effort and flow variables at the two ports are causally related by:

$$e_1 := me_2; f_2 := (\rho m) f_1 \tag{3}$$

or

$$e_2 := e_1/m; f_1 := f_2/(\rho m). \tag{4}$$

As such, ρm is the kinematic scaling between the two flow variables.

Similarly, for $PGY(r,\rho)$, a power scaling gyrator with gyrator modulus r and power scaling ρ in Fig.1, the relationships between the effort and flow variables are:

$$e_1 := r f_2; e_2 := (\rho r) f_1 \tag{5}$$

or

$$f_1 := 1/(\rho r)e_2; f_2 := (1/r)e_1. \tag{6}$$

For unity power scaling (i.e. $\rho = 1$) $PTF(m,\rho)$ and $PGY(r,\rho)$ reduce to regular transformers and gyrators.

A bond graph with power scaling transformers / gyrators is said to be *singly connected* at a $PTF(m,\rho)$ or $PGY(r,\rho)$ if the graph is separated into two disjoint subgraphs when the element is removed. In other words, there should not be any loops containing the element.

The following theorem states that a bond graph with power scaling elements has similar passivity property as a regular bond graph as long as it is singly connected at each non-unity power scaling element.

Theorem 1. A power scaling transformer $PTF(m,\rho)$ or a power scaling gyrator $PGY(r,\rho)$ are conserving with respect to the ρ-scaled power input in the sense that:

$$s(f_1, f_2, e_1, e_2) := \rho f_1 e_1 + (-f_2 e_2) = 0. \tag{7}$$

Here, the power directions are as shown in Fig. 1. Therefore, a power scaling transformer / gyrator is passive with $s(\cdot,\cdot,\cdot,\cdot)$ as the supply rate.

Moreover, if a bond graph with power scaling transformers / gyrators but no active bonds is singly connected at every non-unity power scaling transformer / gyrator, then with respect to input bonds $i_1, i_2, \ldots, i_k$ (assuming all the sign convention of all input bonds correspond to power input into the system when the variables are positive), there exist power scalings $\rho_1, \rho_2, \ldots, \rho_k$ such that the system is passive respect to the supply rate:

$$s(f_{i_1}, \ldots, f_{i_k}, e_{i_1}, \ldots, e_{i_k}) := \sum_{j=1}^{k} \rho_j f_{i_j} e_{i_j}. \tag{8}$$

In order words, given a set of initial conditions, there exists c s.t. for any inputs, and for any time $t \geq 0$,

$$\int_0^t s(f_{i_1}(\tau), \ldots, f_{i_k}(\tau), e_{i_1}(\tau), \ldots, e_{i_k}(\tau)) d\tau \geq -c^2.$$

PROOF. Remove the power scaling transformers and gyrators to form k_m disjoint bond graphs. For bond graph $i \leq k_m$, associate an energy storage W_i to be the sum of the storages of all the $I-$ and $C-$ elements in the bondgraph. Let s_i be the supply rate for each disjoint bond graph with which it is passive. Now, recursively re-insert the power scaling transformers and gyrators one-by-one, by combining two bond graphs at each step. At each step, two passive systems represented by two bondgraphs are connected. If the storage functions of the two bond graphs connected to port 1 and port 2 of the transformer / gygrator are T_{l1}, and T_{l2} respectively, their supply rates are s_{l1} and s_{l2}, and the power scaling of the transformer / gyrator is ρ_l, then 1) define the storage function of the combined bond graph to be $T_l = \rho_l T_{l1} + T_{l2}$; and 2) define the supply rate to be $s_l = \rho_l s_{l1} + s_{l2}$. It is easy to show that using T_l as the storage function, the combined bond graph is passive with s_l as its the supply rate. Continue this process until the original bond graph is reconstituted. It is clear that the final supply rate is of the form (8) and the complete reconstituted bondgraph is passive with respect to it. □

Remark: Notice that the condition for singly connectedness at the PTF/PGY is needed to disallow loops that can cause positive feedback. For example, the bond graph in Fig. 2 is not singly connected at the PTF. It dynamics are given by

$$I \frac{d}{dt} f_1 = (1 - 1/\rho) f_1 + u,$$

where u is the input effort. Therefore, the system is neither passive nor stable, when $\rho > 1$.

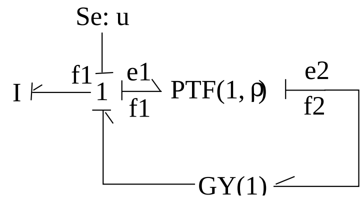

Fig. 2. A non-passive bondgraph with power scaling transformer that is not singly connected.

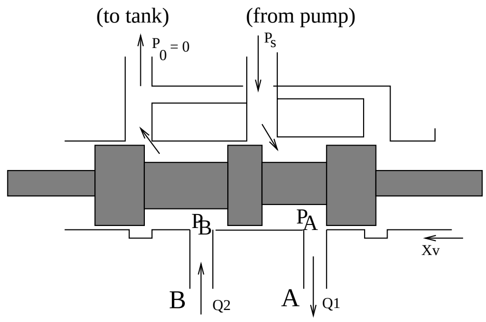

Fig. 3. A typical four-way directional control valve.

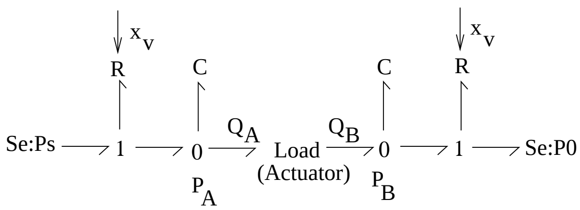

Fig. 4. Bond graph of the hydraulic portion of the valve

4. BOND GRAPH MODELS OF A FOUR-WAY DIRECTIONAL CONTROL VALVE

Figure 3 shows a typical critically centered, matched, four way directional control valve. By actuating the spool, the orifices in the valve are modulated to meter the out-going flow to the hydraulic actuator, and the return flow from it. Assuming the hydraulic actuator is flow conserving (e.g. in a double ended cylinder), and neglecting flow forces and valve chamber dynamics, a mathematical model of the valve is given by (Merritt 1967)

$$m\ddot{x}_v = F \tag{9}$$

$$Q_L(x_v, P_L) = \frac{C_d w}{\rho} x_v \sqrt{P_s - \mathrm{sgn}(x_v) P_L} \tag{10}$$

where F is the total longitudinal force experienced by the spool, which can be controlled using an electromechanical / solenoid actuator; x_v is the spool displacement; m is the spool inertia; C_d and w are the discharge and area gradient coefficients of the valve; P_s is the supply pressure; and P_L is load pressure (differential pressure between the actuator ports); $\mathrm{sgn}(\cdot)$ denotes the sign function. Eq.(10) is applicable when $\mathrm{sgn}(x_v)P_L < P_s$ which is the usual scenario. A similar expression can be written for the common situation when $\mathrm{sgn}(x_v)P_L \geq P_s$.

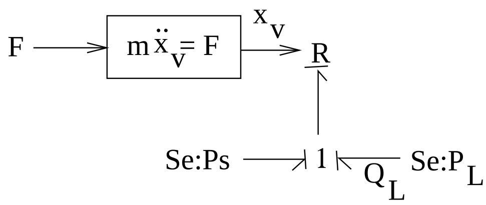

Fig. 5. Simplified bond graph of the valve.

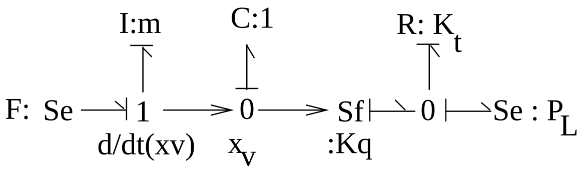

Fig. 6. Active bondgraph representation of 4-way directional control valve

The bond graph model for the valve can be decomposed into the spool dynamics part, and the hydraulics part. The spool dynamics is simply the dynamics of an inertia. A bond graph of the hydraulics portion, with the assumptions of incompressible flow and that of the load being flow conserving (i.e. $Q_A = Q_B = Q_L$), corresponding to Eqs. (9)-(10), is shown in Figure 5 where $P_L = P_A - P_B$ is the load pressure. From this model, it is clear that whenever $x_v \neq 0$, it is possible to manipulate the load pressure P_L so that the pressure source $S_e : P_s$ delivers power to the external environment. In other words, as far as the external environment is concerned, the valve is not passive. Of course, the valve would be passive if pressure source $S_e : P_s$ were also considered part of the external environment.

Despite its direct physical correspondence, the bond graph models in Figs. 4 and 5 are not convenient for the interpretation of passivity from the perspective of control, because as far as the external environment and the control system are concerned, $S_e : P_s$ is part of the system, and cannot be directly affected by the modulating variable (F or x_v). Thus, the presence of this source element would suggest that the system is always non-passive no matter what control is applied to the system.

Following (Li 2000), an alternative representation that is more suitable for bond graph passivity analysis is obtained by first reformulating the flow equation (10) to be

$$Q_L(x_v, P_L) = K_q x_v - K_t(x_v, P_L) P_L \tag{11}$$

where $K_q = C_d w \sqrt{P_s/\rho} > 0$, and $K_t(x_v, P_L)$ can be shown to be non-negative. Thus, we can think of the valve as being a flow source modulated by x_v, in parallel with a conductance that shunts flow. The corresponding bond graph model is shown in Figure 6. Here, the spool displacement is determined by the spool inertia dynamics. In this perspective, the goal of passification is to modulate the effort source $S_e : F$ (in Fig. 6) with a feedback control so as to make the system appear passive to the external environment.

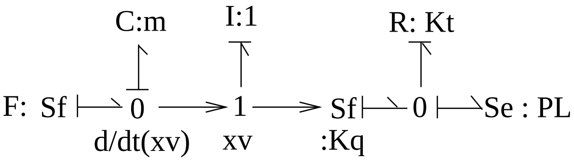

Fig. 7. Dualized active bondgraph representation of 4-way directional control valve

5. BOND GRAPH APPROACH FOR PASSIFICATION

Notice that the bond graph in Fig. 6 contains two signal bonds: one associated with the modulating effect of the spool displacement x_v on the flow rate; the other associated with the integration of the spool velocity $\dot{x}_v$ to obtain the spool displacement x_v. The main idea in our approach of passification of the valve is to replace these active signal bonds by passive power bonds or power scaling transformers / gyrators. We proceed in three steps:

Step 0: Duality transformation Transforming the spool dynamics portion of the bond graph in Fig. 6 using the duality relationship, we obtain the bond graph in Fig. 7.

Step 1: Create a desired bond graph by first replacing active signal bonds and modulated effort / flow sources by power scaling transformers.
The power scalings γ_1, γ_2 of the two PTF's and the modulation factor r_2 of the PTF that replaces the "integrator" signal bond are to be determined later. The modulation factor of r_1 of the PTF in the x_v induced signal bond must be chosen to be K_q/γ_1 to preserve the meaning of the flow variable at the "1" junction to remain to be x_v.

Notice that dualization step in Step 0 can be avoided if we choose to replace the active bonds by PGY instead of PTF. We prefer to use PTF because they reduce to simple power bonds when both the modulation factor and the power scaling are unity. In this sense, they are more natural.

Step 2: Add other regular or power scaling bond graph elements.
One possibility is to add an effort source F_x' at the "1" node as an auxiliary control input, and add a R-element "B" at the left hand most "0" junction. The resulting bond graph is shown in Fig. 8. Notice that Fig. 8 is a bond graph with power scaling components but is singly connected at these components. Therefore by Theorem 1, the system represented by this bond graph is passive with respect to a supply rate:

$$s(F_x', P_L, x_v, Q_L) = \gamma_1 F_x' x_v - P_L Q_L.$$

Step 3: Determine the appropriate spool dynamics that realize the desired bond graph.
Label the effort variable in the 0 junction by z. Then, according to the bond graph in Fig. 8, the dynamics of x_v and of z are given by:

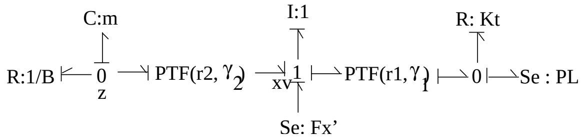

Fig. 8. Desired power scaling bond graph representation of 4-way directional control valve with active bonds replaced by PTF / PGY.

$$\dot{x}_v = \frac{1}{r_2} z + (F_x' - r_1 P_L) \tag{12}$$

$$m\dot{z} = -\frac{1}{\gamma_2 r_2} x_v - Bz \tag{13}$$

Notice that (12) gives the transformation z given by:

$$\frac{z}{r_2} = \dot{x}_v - (F_x' - r_1 P_L).$$

Differentiating (12) and utilizing (13), we obtain the spool dynamics necessary to realize the dynamics of the bond graph to be

$$m\ddot{x}_v = m\frac{d}{dt}(F_x' - r_1 P_L) - B\frac{z}{r_2} - \frac{1}{\gamma_2 r_2^2} x_v.$$

Substituting the expression for z, we have:

$$m\ddot{x}_v = -B\dot{x}_v - \frac{1}{\gamma_2 r_2^2} x_v - B(F_x' - r_1 P_L) + m\frac{d}{dt}(F_x' - r_1 P_L). \tag{14}$$

Comparison between (14) and (9) suggests that the *ideal* passification control law should be of the form:

$$F = -B\dot{x}_v - Kx_v - B(F_x' - r_1 P_L) + m\frac{d}{dt}(F_x' - r_1 P_L), \tag{15}$$

where $K = 1/\left(\gamma_2 r_2^2\right)$. Consider now the closed loop system with (F_x, x_v) and (P_L, Q_L) as the input port variables. Following the proof of Theorem 1, we can choose

$$W = \gamma_1 \gamma_2 \frac{m}{2} z^2 + \frac{\gamma_1}{2} x_v^2 \tag{16}$$

to be the storage function of the system, so that the system can be shown to be passive with respect to the supply rate:

$$s_{valve}(F_x', P_L, x_v, Q_L) := \gamma_1 F_x' x_v - P_L Q_L.$$

Step 4: Adding robustness
The control law requires estimating the derivative of $F_x' - r_1 P_L$. Generally, there will be an estimation error which can be considered flow source at the "0" junction. To combat its effect on passivity, we can add a dissipative term to ensure that the system dissipates more energy than it might possibly gain from the estimation error (Fig. 9). Assuming that we can estimate the bound for the estimation error:

$$\left| \frac{d}{dt}(F_x' - r_1 P_L) - \widehat{\frac{d}{dt}}(F_x' - r_1 P_L) \right| \leq b_{err}, \tag{17}$$

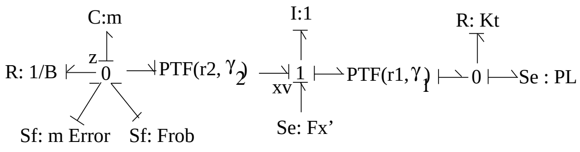

Fig. 9. Bond graph of passified valve with robustness modification and estimation error.

where $\widehat{d/dt}(\cdot)$ is the estimate of the derivative of the argument, the passification control law can be modified to include the term:

$$F_{rob} = -m\text{sgn}(z)b_{err}.$$

This ensures that $F_{rob}z + \text{Error} \cdot z \leq 0$ for any estimation error $\text{Error}(\cdot)$ (the signal inside $|\cdot|$ in (17)) satisfying its assumed bound.

Let $\gamma > 0$ and $A > 0$ be two constants. If we choose,

$$r_1 = \frac{A}{B}, \qquad \gamma_1 = K_q/r_1 = K_qB/A;$$
$$r_2 = 1, \qquad \gamma_2 = 1/(\gamma B),$$

and define $F_x := B \cdot F_x'$, then the active passification control law in (Li 2000) is recovered exactly.

The closed loop transfer function of the valve passified using this set of parameters is of the form,

$$x_v(s) = \frac{s + B/m}{B\left[s(s+B/m) + \gamma B/m\right]}\left[F_x(s) - AP_L(s)\right]. \tag{18}$$

The bond graph in Fig.8 seems to depend on five parameters, $r_1, \gamma_1, r_2, \gamma_2$ and B. However, there are 2 constraints, namely, $r_1\gamma_1$ must equal K_q, and γ_2 and r_2 appears only $K = 1/\left(\gamma_2 r_2^2\right)$. Therefore, only 3 parameters can be used independently to adjust the passification control law. The bond graph in Fig. 8 is exactly equivalent to the original passification algorithm, parameterized by A, B and γ or $K = 1/(\gamma B)$. Notice that A, B and K have physical interpretations of area for load pressure feedback, spool damping coefficient, and spool centering spring rate respectively.

6. GENERALIZATION

The bond graph approach offers potentially new ways to passify the valve. For example, an alternate bond graph structure can be used. So, if instead of the bond graph in Fig. 8, the bond graph in Fig. 10 in which a general admittance $Y(s)$ as well as an additional input F_1 are attached to the "0" node can be imposed, and a general impedance $Z(s)$ and an input F_x are attached to the "1" node. The generalized structure may alleviate the tradeoff between dissipativeness and bandwidth that the original passified valve structure has. From (18), we see that to achieve large bandwidth, one should use a large B. However, this also contributes to small gains from $F_x - AP_L$ to x_v, leading to excessive apparent energy loss. In an haptics environment, energy dissipation appear as a damping term (see (Li and Krishnaswamy 2001)) which adversely affects the way the human perceives and distinguishes

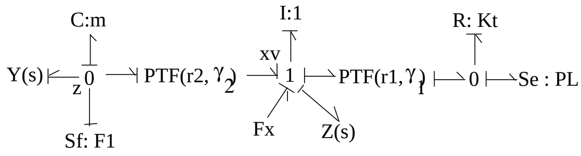

Fig. 10. Alternate bond graph structures for passification

the external environment. The flexibilities afforded by the different structures and the possibility of using *dynamic* elements may be helpful in alleviating such limitations by shaping the frequency response of the passified valve. These issues will be investigated in the future.

7. CONCLUSION

In this paper, we investigated the passivity property and the passification of a directional hydraulic control valve from a bond graph perspective. In addition, two bond elements - power scaling transformers / gyrators are introduced. It is shown that following several bondgraph transformations and after the replacements of signal bonds by power scaling transformers and gyrators, the previously discovered passification control law for the valve can be recovered and generalized. This methodology may be useful for the passivity analysis and passification of other control systems.

REFERENCES

Colgate, J.E. (1994). Coupled stability of multiport systems-theory and experiments.. *Transactions of the ASME. Journal of Dynamic Systems, Measurement and Control*, **116**(3), 419–28.

Huang, S. Y. and K. Youcef-Toumi (1999). Zero dynamics of physical systems from bond graph models -Part 1: SISO system. *ASME Journal of Dynamical Systems Measurements and Control* **121**, 19–26.

Li, Perry Y. (2000). Towards safe and human friendly hydraulics: the passive valve. *ASME Journal of Dynamic Systems, Measurement and Control* **122**(3), 402–409.

Li, Perry Y. and Kailash Krishnaswamy (2001). Passive bilateral teleoperation of a hydraulic actuator using an electrohydraulic passive valve. In: *Proceedings of 2001 American Control Conference*. pp. 3932–3937.

Li, Perry Y. and Roberto Horowitz (1997). Control of Smart Exercise Machines: Part 1. Problem Formulation and Non-Adaptive Control. *IEEE/ASME Transactions on Mechatronics* **2**(4), 237–247.

Merritt, Hebert E. (1967). *Hydraulic Control Systems*. John Wiley and Sons.

Ngwompo, Roger F. and Peter J. Gawthrop (1999). Bond graph-based simulationof nonlinear inverse systems using physical performance specifications. *Journal of the Franklin Institute* **336**, 1225–1247.