MODELING OF THE CVT IN A VIRTUAL ENGINEERING ENVIRONMENT

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In this paper a *Virtual Engineering Environment* (VEE) will be characterized. It will be shown that bond graphs are a good choice as a modeling tool for mechatronic products like the Continuously Variable Transmission (CVT) in a VEE. With this tool it is possible to split up the pure system modeling tasks from the computational and analysis aspects of a design and control problem. This results in an explicit way of investigating the appropriateness of the proposed model and this at the very first beginning of the modeling phase. Also the derivation of a desired mathematical model can be cast when necessary and some structural properties which influence further designs can be answered.

INTRODUCTION

Figure 1 shows the software feedback loop of a future Digital controlled Continuously Variable Transmission (D-CVT).

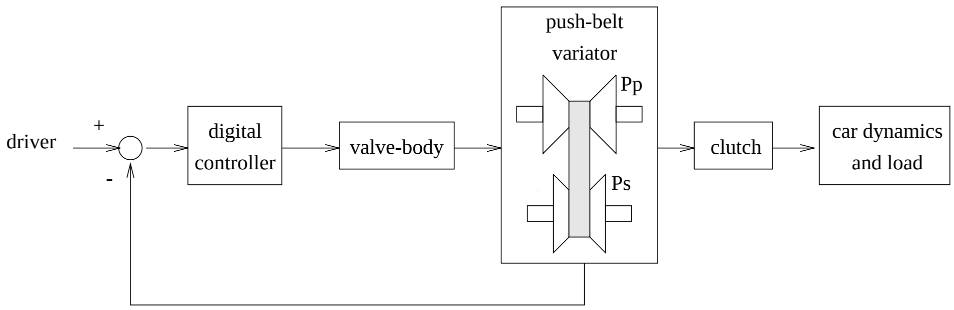

Figure 1: *The software feedback loop of a D-CVT.*

The heart of this type of transmission is made of a metal push-belt interfacing two conical pulley sheaves. The transmission ratio can be set continuously by positioning the push-belt somewhere on the sheaves. A digital controller monitors and controls the behavior of the push-belt [Minten, 1993], and an hydraulic servo system, called *valve body* interfaces the digital controller and the push-belt variator.
Therefore an ensemble of engineering tools has to be used for the development of a (sub)optimal solution in the sense of development cost and time, and system performance. These constraints result in a different engineering approach than the classical *trial and error* based design methods. One of the major drawbacks of a classical design is the fact that such a real prototype based approach is not very well

suited for fast and cheap evaluation of new designs. Therefore a severe improvement of this design method is the statement that any hardware experiments must be excluded, or at least delayed as much as possible. Obviously hardware experiments are nevertheless essential for unknown data capturing and validation.
To achieve this computers and appropriate calculation models are needed for simulation, analysis and design purposes of the system. Although this way of dealing a design is necessary, it can again be improved by aiming that these software experiments must be excluded, or at least delayed as much as possible. On the other hand such software experiments are nevertheless essential for data optimization and sensitivity analysis of a design.
In order to satisfy these needs a modeling method must be chosen that can answer questions on the model quality level, subsequent parameter and structure constraints, mathematical formulation constraints,.... In this paper it will be shown by example that bond graphs [Karnopp, 1990] answer to these questions and hence are a good choice as modeling method.
In figure 2 a general framework is shown where the proposed methods fit into one ensemble named a *Virtual Engineering Environment* (VEE). This figure shows the flow from an initial *design in mind* to an optimal (controlled) system. Sometimes only a design of the physical structure is desired (left flow), but most of the time the performance of such a system must further be optimized in order to satisfy some closed loop characteristics (left and right flow). This figure is a rather general one and can serve for every type of mechatronic product design. Notice that until now most controller design methods are based on linear models and hence at a certain stage a linearizing of the real system structure must be done. Mostly this linearizing takes place *after* an optimized system design has been obtained, especially when the nonlinear effects influence largely the operating points of the system. Notice also the summator blocks and the dashed (computer) experiments. They indicate a validation procedure step in the VEE. When this validation does not influence higher points in the flow, subsequent design modifications will not influence previous actions on the design. This is really one of the major characteristics of a VEE. However, in some control design cases the choice of appropriate sensors or actuators is made after the system design phase. Consequently a recapitulation of the system design sometimes seems unavoidable.
In this paper this way of virtual engineering will be explained by means of the D-CVT. In the next section the constraints on the modeling tool from a VEE perspective will be outlined. In the third section it will be shown that the bond graph characteristics answer to these constraints and therefore can be used as the modeling tool in a VEE.

ASPECTS OF MODELING IN A VEE

In what follows some modeling aspects in a virtual engineering framework are proposed. This will not be done with an exhaustive and comprehensive list of more or less important characteristics. In fact the items explained below are highlighted because they played an important role in the development of the VEE for the D-CVT.

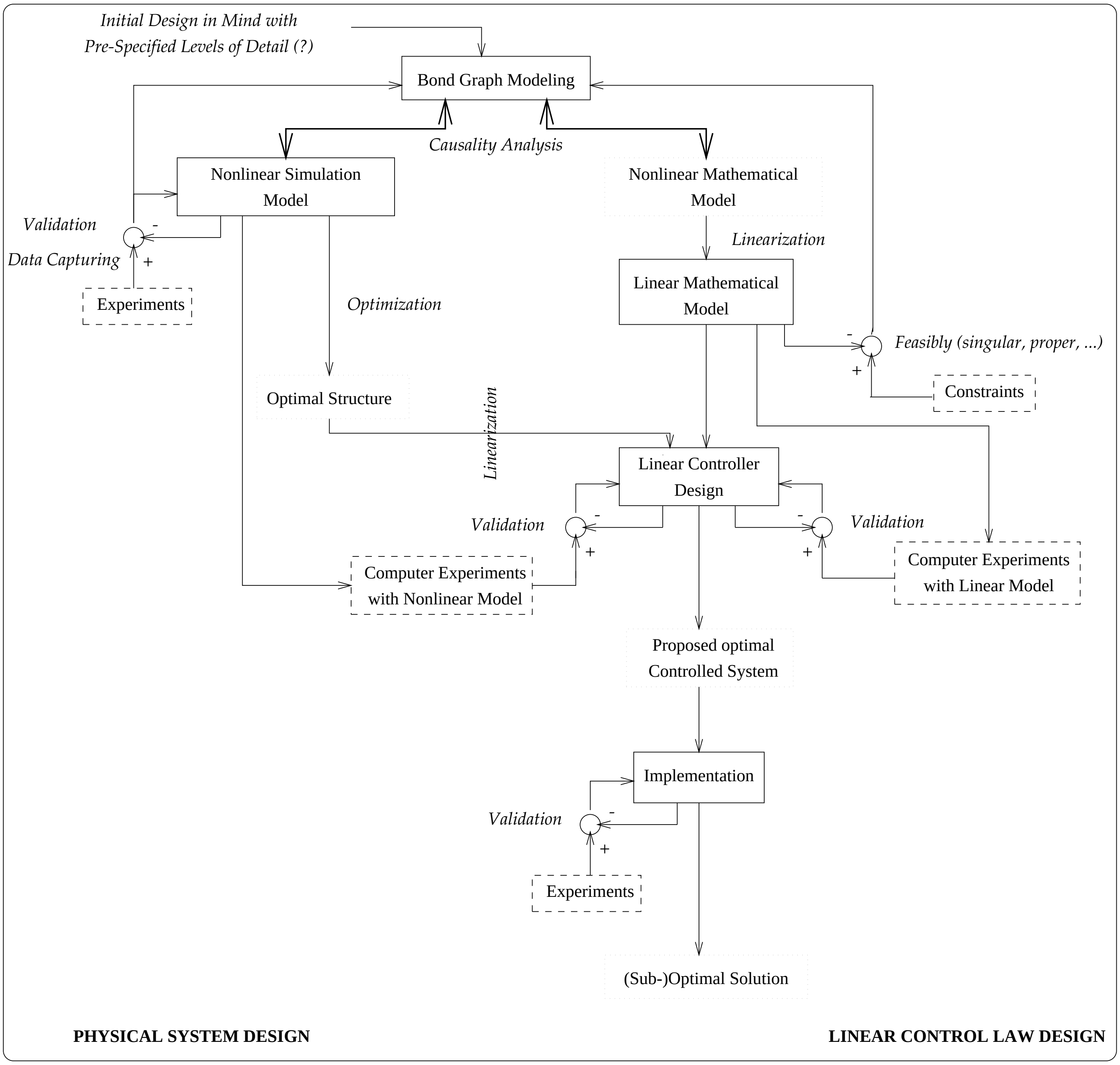

Figure 2: *The construction of a Virtual Engineering Environment.*

The shortest way towards right designs

In the introductory section of this paper it has been shown that an important characteristic of a VEE is the ability of doing a right design *at the first time* or at least as soon as possible. The speed of obtaining a good design depends on the speed of gaining knowledge of the system. Consequently, one has to obtain as soon as possible in the development phase of a design the relevant system characteristics in order to make the right decisions at the right time. This avoids for example very expensive backtracking traces in the development of new mechatronic products. Since modeling is invoked at the first beginning of the design, the modeling method determines to a great extend the over-all quality of the VEE.

Model complexity and accuracy

In order to create a physical structure with certain pre-specified characteristics and performance, one needs powerful methods and tools for simulation of the system behavior, design of software prototypes and eventually, tuning some free controller parameters. This seems an acceptable and achievable task list of a VEE. However, such a task list invokes different aspects of the mathematical model under consideration and therefore, in the past different mathematical models of the system are derived with different methods and tools, and this for the different purposes. Each of these methods and tools were fit for use in certain cases, but are completely not workable in other. This can be illustrated as follows. The system design engineer has to observe physical relevant properties of the system in mind. Different *modeling* based methods exist in order to formulate appropriate mathematical models. Most of the time these models are nonlinear and therefore a simulation environment could serve for observing and analyzing the system behavior in time. However for most control design aspects of the same system linear models based on *identification* procedures are derived. Such models fit easily in several linear control design schemes and therefore are preferred by most control engineers. In industry and research institutes it is amazing that a large incomprehension exists between them. This originates from the fact that a design engineer has to consider the physical part of the system much more in detail than a control engineer does. Models derived for system design typically have a large bandwidth, and models derived for control design typically have a small bandwidth. This way of viewing the same physical system is influenced by the well known *feedback loop* configuration of a controlled system, a configuration which is able to deal with the uncertainty of characteristics of the forward path, where the system is also a part of. System nonlinearities and high frequency information of the underlying system can be seen as such and therefore are of secondary importance for most control problems.
Remark that none of these models are *wrong* as such, they only fit better into a certain engineering perspective. It is the aim of a VEE that the proposed models of a system can be used for both system design and control design perspectives. Therefore some model transformation tools must be available in order to cope with different accuracy and complexity of the models.

Mechatronic modeling

Since mechatronic products are typically made of mechanical, electrical and hydraulic parts, it is necessary that these parts are cast from a *system engineering* *viewpoint*. This makes it possible to consider the same physical effects in the different domains alike. This saves engineering time and invokes a better understanding of the system behavior, even before any system simulation.

Sub-structuring

In order to shorten the development time of a dynamic model of the system, it is necessary that the modeling tools posses sub-structuring facilities. This should make it possible to use pre-build models in a constructive and hierarchical way. This way of modeling offers also an explicit means for dealing model accuracy in a fast and elegant way, because different models of the same (sub-)system can be made and archived for later use.

CAPABILITIES OF BOND GRAPHS AS MODELING TOOL

To some extend every modeling method offer the aspects mentioned in the previous section. However, as will be shown in the sequel, the bond graph method is far more appropriate to function in a VEE. Due to space limitations the reader is referred to [Karnopp, 1990] for a detailed explanation of the bond graph method. This appropriateness will not be illustrated by comparing bond graph modeling with other modeling methods, but simply by observing how a bond graph can answer to the proposed aspects and properties of modeling of the D-CVT in a VEE.

Causal assignment as the basis for analyzing the model

Consider a first yet very informative model of the translation part of the variator of the CVT [Minten, 1995/2], shown in figure 3 (a).

This model can be used for both system design and control design perspectives. If the system designer only is interested in simulating and watching the system behavior in time, then the constituent relations of the system can be derived and used as input in a simulation program like ACSL or SIMULINK. Depending on the structure of the equations (DAE's, ODE's) and the parameters (linear, nonlinear, stiff, ...) appropriate integration algorithms must be used in order to calculate appropriately the system behavior in time. For this kind of analysis, automatic processing of the set of constituent relations towards a simulation program can be done with pre-processors like DYMOLA.

However, other analysis aspects could be important for the designer. Therefore causal assignment offer structural aids in revealing relevant system properties. Basically this assignment transforms the constituent relations into assignment statements. According to the kind of causal assignment used one gets different mathematical formulations of the same system, each of them best suited in certain circumstances. An important causal assignment procedure is the Sequential Causal Assignment Procedure [Rosenberg, 1983], usually denoted as (all-integral) SCAP. This has been done in figure 3 (b). Take for example the belt spring constituent relation, $\frac{dF}{dt} = \frac{1}{C}(\dot{x}_p + \dot{x}_s)$, with $C = \frac{1}{k_b}$. The assignment statement can be written in integral or differential form, the first form looks like $F := \int \frac{1}{C}(\dot{x}_p + \dot{x}_s)dt$, which means that the spring force has been calculated from the right hand side of the equation. The calculated variable is in bond graph terms an *effort variable* and the direction where this variable goes to in the bond graph is graphically shown with a flat *effort arrow*. When using the (all-integral) SCAP procedure the modeler follows certain rules in making this causally augmented bond graph [Rosenberg, 1983]. One notices on the augmented bond graph that no storage element (the two inertias m_p and m_s, and the single spring k_b) forces another in derivative causality, and hence the system is not degenerate. If supplementary there is no causal indeterminacy between non-invertible dissipators, a set of explicit ODE's (state space form) can be derived [Minten, 1995/1],

$$\dot{x} = \varphi(x, u) \tag{1}$$

and the number of states (components of x) equals the number of storage elements in preferred integral causality (3 in this case).

In the all-derivative SCAP procedure [Karnopp, 1983/1], shown in figure 3 (c), the storage element m_p forces the other storage element m_s in non-preferred causality. This reveals a dependency between the rates (state velocities) in the autonomous case of Equation (1). If the system would be linear than the system matrix A of the state space description is singular. This form of causally augmented bond graph is also useful in deriving transfer function poles and zeros for such linear systems. Explicit calculation can be done with the Mason Loop rule [Brown, 1972]

$$H_{ij} = \frac{\sum\limits_k P_{ij_k} \triangle_{ij_k}}{\triangle} \tag{2}$$

However, at first sight already some structural properties of the transfer function can be found as follows: If all the storage elements appear in preferred (derivative) causality, then all the path and loop gains are constructed of only admittances, and hence $\sum_k P_{ij_k} \triangle_{ij_k}$ is directly the numerator polynomial and $\triangle$ the denominator polynomial of the transfer function. Similar statements can be made when non-preferred causalities appear [Minten, 1995/2]. Consider for example the transfer function $\frac{\dot{x}_s}{p_p}$. The non-preferred causality of m_s appears in the forward path from p_p to $\dot{x}_s$. This results in a pole at the origin. There are three causal paths, a zeroth order (m_p to m_s), a first order ($\frac{1}{k_b}$ to R_b) and a second order (m_p to $\frac{1}{k_b}$). Hence the denominator polynomial is of degree 3 (three poles) since supplementary all loops or products of non touching loops have a highest degree in s of 2. There is also one zero since only the first order loop is not touching the forward path.

Remark that these statements are made after a bond graph sketch of the system in mind has been made and after certain causality procedures have augmented the bond graph. A lot of simulationists claim that all this work of assigning causality is wasted time since good computer programs are available to do that job. And in fact, in their opinion they are right. However a design engineer is not only interested in simulations or equations. He wants to have as much as possible *feeling* with the model. With bond graphs the real modeling is done with the observation of energetic properties which can be cast in a system engineering viewpoint, and the analysis starts with assigning causality on the bond graph. Today no software program is available to do that job better than the *paper and pencil* method. In a VEE appropriate software should be available to accept the non-causal bond graph and warn the designer for certain modeling implications or assumptions that has been made, and eventually modify them *interactively*. Only then the designer gains insight in what he is doing, and what the consequences of his acts are. This learning is really an aid in validating subsequent simulations. With the explicit use of causality the modeler gains experience, which still is the best teacher. This experience cannot be gained with other modeling methods or automatic formula generation programs. Only after such a first design has been done the parameters become important, and consequently simulations and other explicit mathematical formulations are of interest of the design and control engineer. In what follows this will further be illustrated to some extend.

Better control of the transmission ratio
Till now it is assumed that the servo system acts in some way like ideal pressure sources. It should be interesting to know in advance what the impact will be of designing a servo system which behaves more like ideal flow sources. All-integral and all-derivative SCAP, shown in figure 3 (d), reveals in both cases the same causal form of the storage elements, the inertias in derivative and the belt spring in integral causal form. Hence the state space dimension is reduced form three to one, and no singularities of the autonomous state equation occur. Remark that the derivative causality of the inertia of the sheaves is forced by the sources, and hence their physical effect play no role at all in the state equation (they simply do not appear in that equation). This knowledge is important in robust control aspects of the D-CVT for which uncertainties on the inertias could be important. However, practically spoken the push-belt parameters are more uncertain, and the causal bond graph reveals that these parameters cannot be excluded structurally. This is only possible when an extra ideal effort source can be introduced at the 0-junction, what is impractical.

Quality of the sources While using the all-integral SCAP, the sources in figure 3 (d) force the inertia of the sheaves in derivative causality. This indicate that these sources are less natural than the effort sources shown in figure 3 (b) since discontinuous changes of the inlet flow result in infinite pressure changes at the inertias of the sheaves and hence the sources should be able to produce an infinite amount of power. This power constraint is really a design problem for such sources and must be observed carefully in further designs.

Abstraction level of the push-belt In the bond graph one can easily see the impact of changing some other modeling assumptions, like the assumed dynamics of the push-belt. Centrifugal forces of the push-belt influence the contact force between push-belt and the sheaves, and hence can result in belt slip. The proposed model of the belt is simply not rich enough to cope with these aspects. Modified models of the push-belt can simply be plugged in between the two 1-junctions where the inertias stand on. Such a modularity is of great advantage during modeling of the dynamics. A very simple example of this is shown in figure 3 (e) where it is assumed that the important belt dynamics are located in a frequency range beyond the scope of interest and that the belt losses can be neglected. This change in abstraction level of the push-belt (which can be argued as the *ideal* design) reveals a different bond graph comparing to the one in figure 3 (b). It reduces the number of states with two, since there exists a causal path between the inertias.

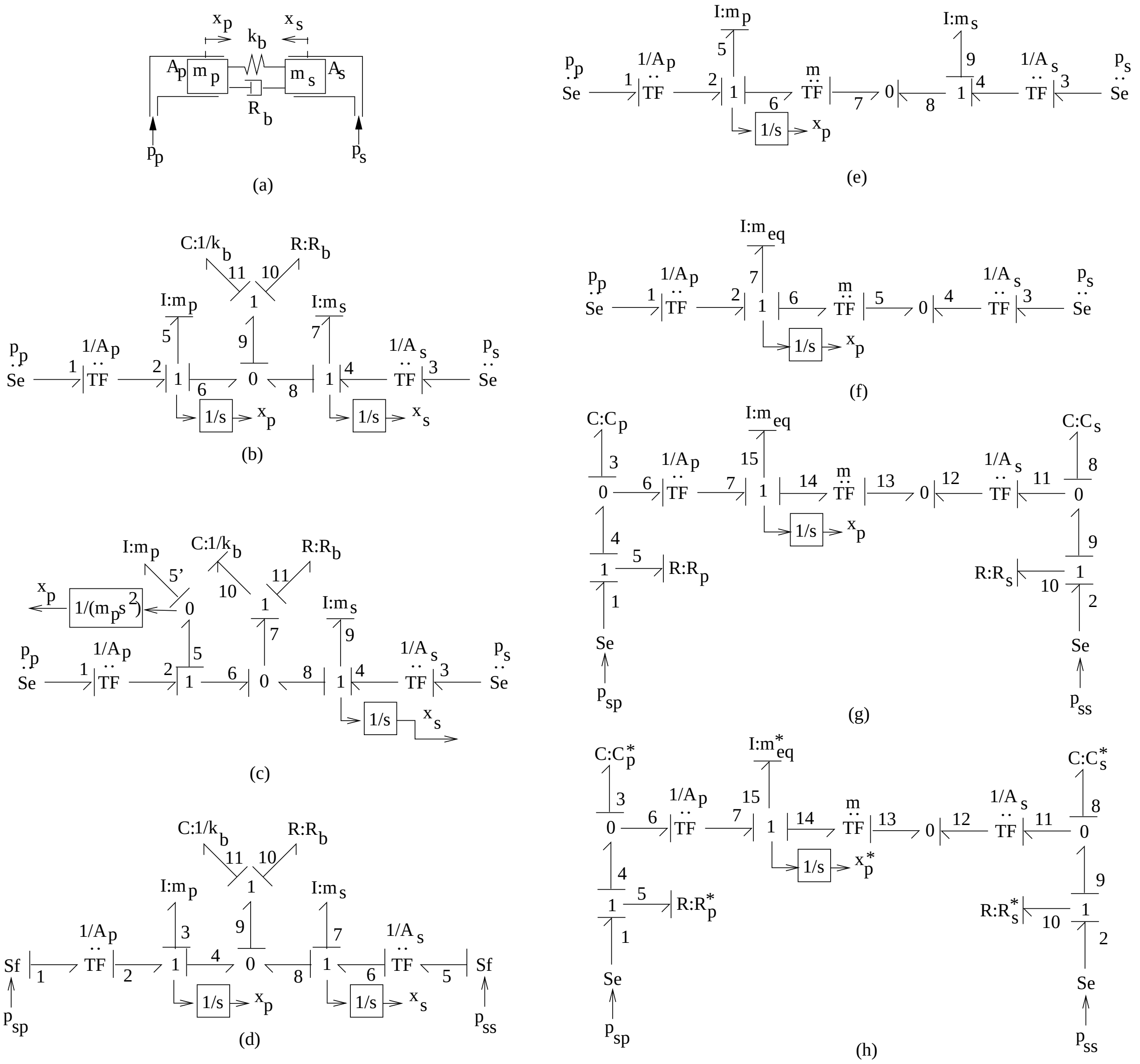

Figure 3: *(a) Physical model of the CVT. At this stage the translation behavior of the sheaves of the push-belt variator is under consideration. In this physical model expected major dynamic effects are considered. The push-belt is modeled by a spring* k_b*, whereas its position on the sheaves can be modeled as stemming from the inertias* m_p *and* m_s*. Losses, mainly friction between the push-belt and the sheaves, are modeled with the dissipator* R_b*. The position of the sheaves can be set by means of an hydraulic servo system, modeled as two pressure sources* p_p *and* p_s*.*
(b) Causal bond graph after the procedure SCAP. The bonds are numbered according to the sequential assignment of the causal strokes.
(c) Causal bond graph after the all-derivative SCAP procedure.
(d) Influence of the use of flow valves instead of pressure valves.
(e) Influence of neglecting high frequency information and dissipation of the push-belt.
(f) A possible model transformation on the bond graph level.
(g) Influence of a non-ideal pressure inlet.
(h) Linearisation on the bond graph level.

Modeling assumptions
Derivative causality can result from simplifications made by the modeler. Such simplifications can be made deliberately or unconscious, allowed or un-allowed. Bond graphs give no answer to this kind of questions. However it points out explicitly some of these simplifications. An example of this is shown in figure 3 (e) where the non-preferred causality of the inertia m_s stems form neglecting the belt stiffness. If such situations are due to an oversimplification, forgotten dynamics can be included.

About model transformations
It should be noted, despite of the non-preferred causality, that models like shown in figure 3 (e) can be used for deriving a simulation model, either by hand or with computer aid. Again this last one is useful for simulation purposes. The zeroth order causal path from m_p to m_s can be cast numerically or symbolically. This symbolic manipulation of the equations can be made explicitly on the bond graph level, and hence has the benefit of giving physical interpretations of the symbolic manipulations. An example of such bond graph level manipulations is shown in figure 3 (f), where the inertia m_s is transformed to the left side of the TF.
Another physically based method is the so called Karnopp-Margolis method [Margolis, 1993] which re-considers the irrelevant dynamics, denoted as parasitic dynamics, to break the causal path. Good use of this method result in stiff systems, which is not beloved by simulationists.
Other dynamic effects which are neglected during modeling are the inlet and outlet dynamics of the hydraulic part of the sheaves. Here the pressure in the oil chambers can change considerably as result of centrifugal forces of the hydraulic oil and the variable oil chamber volume. The effect of the latter one is shown in figure 3 (g). This bond graph is highly nonlinear (nonlinear relations at the inlet and outlet rstriction, and nonlinear state equations of the oil compliance) and is as such unusable in classical control schemes. Rather than linearizing the set of governing equations, it is from a structural point of view more interesting to do the linearizing on the bond graph level [Karnopp, 1983/2]. The resulting linearized bond graph is shown in figure 3 (h) [Minten, 1995/2], [Scavarda, 1993] which can be used as departure of further linearized analysis, design or control. This last method keeps the modeler in touch with the real energetical structure of the system, which again is more informative to the modeler than linearizing a set of nonlinear equations.

CONCLUSIONS

A first part of this paper concerns a possible framework for a VEE. The benefits of using such an environment are numerous. There is a shorter time to market, a cost saving during the R&D phase, the product quality can be improved, and last but not least insights and knowledge are gained for future innovations. The second part deals with the modeling environment of a VEE. It has been shown through example of a D-CVT that bond graphs help the modeler in revealing explicit structural characteristics of the model, and this at the very first beginning of the modeling phase. This structural information is important in system and control design related objectives, it serves as a steering mechanism pointing out some later consequences of modeling activities. It was not the aim of this paper to do the whole design of the D-CVT. For this, the modeler has to proceed with the derivation of the governing equations into a certain desired form, for which references are given to the relevant papers or textbooks. Remark that the role of bond graphs is definitely not finished when the equations are derived. This however is beyond the scope of this paper.

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