VIRTUAL ENVIRONMENT FOR DYNAMIC MODELING OF MULTI-DOMAIN SYSTEMS

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Abstract. *The complexity involved in developing engineering models demands a long learning curve, embracing concepts from areas such as physics, engineering, mathematics, computer science and control. Such breadth of knowledge creates high costs and long period of development even to obtain less representative models. Both industrial and academic environments face this reality. Mainly due to historical reasons, most of activities related to dynamic modeling so far use tools based on signal-port approach, where a single value or an array of values are transferred from one component block to another in a single direction. Such approach was developed mostly for control systems. However, problems arise when power is transmitted, what leads to the need to exchange information between components in both directions, i.e. a multi-port approach. This article demonstrates the experience drawn from research and teaching activities based on AMESim- Advanced Modeling Environment for Simulation. The software has been successfully applied to a natural gas project integrated with expert system, as well as to teach dynamic modeling for applications varying from electrical drivers, fluid power, control and injection systems.*

Keywords: *Dynamic Simulation, Multiport Modeling, AMESim*

1. Introduction

The increasing demand for more competitive products, with higher technological level, has given a continuous emphasis to dynamic modeling by the industrial sector, especially in areas such as aeronautics, car manufacturing and heavy machinery and also by institutions of research and development and academia. Until recently, the complexity of virtual prototyping in dynamic modeling required a long learning curve and knowledge from different domains such as physics, mathematics, computer science, engineering and control theory. This breadth of knowledge resulted on high costs and long development time, even to obtain poor models.

The great challenge was, and in most cases still is, to represent the interaction among the different dynamic phenomena involved, their states relationships, inputs and outputs definitions in a same environment without letting the computation representation becoming too complex to handle.

Another aspect that has continuously brought attention to dynamic modeling is because this analysis brings a better understanding of key events such as surges of electrical current, pressure, flow, force, etc. that, in general, directly affect the durability and maintenance of equipment (Silva and Nascimento, 2002).

As widely known, the theory of simulation provides two paradigms, usually defined as signal port and multiport approaches. Signal port modeling has been more applied, especially because it is greatly spread among the control engineering community, however, as will be shown here, it creates serious problems when modeling systems not limited to control. In the other hand, multiport modeling is far more general than the previous one, and many authors consider that signal port as a special case of multiport modeling (Lebrun and Richards, 1997). Multiport modeling lies on the theory of bond graphs which describes all engineering domain in terms of 9 basic elements, nevertheless due to its inherent complexity the representation of technical systems in a direct bond graphs terminology brings many specific challenges (Karnopp et alli, 1990).

This paper introduces to the engineering community in Brazil an environment that incorporates the main advantages of bond graph, i.e. integration of energy domains and power transmission representation, in a user-friendly interface keeping the modeling complexity in a manageable level, and, at the same time, allowing the possibility of developing sophisticated models according to the users' background. The system known as AMESim- Advanced Modeling Environment for Simulation- is worldly applied to dynamic analysis of engineering systems such as:

- The study of vehicle behavior in various in-motion situations (Parmentier, 2004)
- Engineering design process of heavy-truck unit-injector system (Chaufour et alli 2004).
- Powertrain driveability evaluation (Hayat et alli 2003).
- Natural gas transportation networks modeling (Silva et alli, 2004; Silva Jr. and Silva, 2002).

This article is organized in the following sections. Firstly, a comparison of signal port and multiport approaches is presented in order to demonstrate how multiport modeling can contribute to support teaching of dynamics in multi-domain systems. Secondly, the paper describes some of the main AMESim functions that bring the focus of teaching from the numerical manipulation to other more engineering oriented issues such as causality analysis, power transmission, and system integration. Those issues have as direct consequences: reduction of the need to test physical prototypes, more thorough testing of product, decrease of time to market and a better understanding of the product

(Lebrun and Richards, 1997). Finally, more advanced features, such as model reduction through activity indices analysis in AMESim, are introduced to support the teaching of dynamic modeling.

2. Comparison between Signal port and Multiport Techniques

In the signal port approach, a single value or an array of values is transferred from one component block to another in a single direction. Therefore, this approach is adequate when the physical system behaves in the same way as a control system. However, problems arise when power is transmitted. This is because modeling of components that transmit power leads to a requirement of information exchange between components in both directions. In order to use a signal port approach in this situation, two connections are necessary between the components to model a single physical connection. This limitation leads to a great complexity of connections and it means that even very simple models involving power transmission become too complex to understand, and consequently hard to be transmitted to engineering students.

In contrast to the signal port approach, with the multiport approach, a single connection between two components allows information to flow in both directions. This makes the system diagram much closer to the physical system. Normally there are two values involved and the theory of bond graphs provides a sound theoretical background into the relationship between these values and transmitted power. When there is only one quantity, the situation is equivalent to the signal port. Thus signal port can be regarded as a special case of multiports (IMAGINE, 2000). In order to exemplify the differences between the modeling techniques, Figs. 1a and 1b present the same system modeled respectively by the signal port and by the multiport approaches.

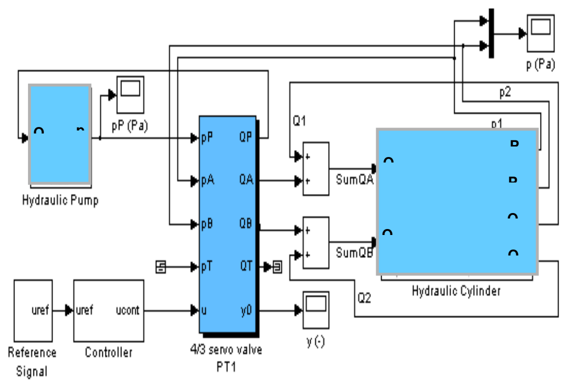


Figure 1- Hydraulic circuit modeled via signal flow.

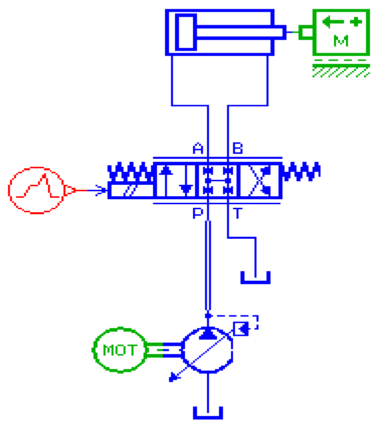


Figure 1b- same circuit modeled in AMESim

As presented before, in the signal port approach, the variables are transferred between the functional blocks, representing in this case different components, in a single direction. Therefore, it is necessary two connections to model the power interaction that takes place in a single physical port. For example, it is known that power is exchanged between cylinder and valve through the interaction of pressure and flow in their respective ports, thus it is necessary one port to send the flow signal from the valve, originated from the characteristic flow equation, to the cylinder. The cylinder, in its turn, via its dynamic behavior processes flow signals as inputs and provides pressure signals to the valve and force signals to the mass component (not shown in fig. 1a). In the other hand, not only does fig. 1b represent the circuit diagram, but in fact it provides in every component the corresponding ports, with implicit causality laws, as seen in figures 2 and 3, respectively cylinder and mass components.

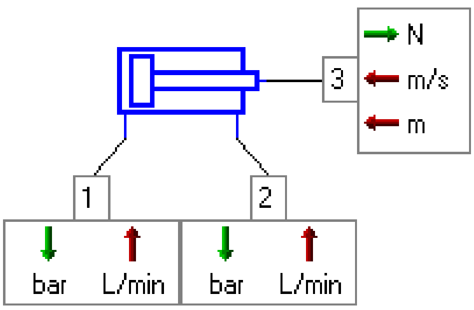


Figure 2. Cylinder model in AMESim.

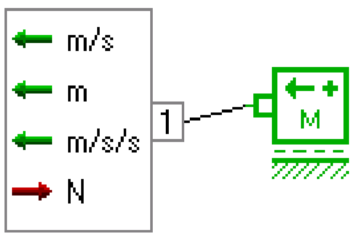


Figure 3- Mass component and its ports.

As figure 2 presents, the cylinder model contains three ports, two in the hydraulic domain and one in the mechanical domain. This model considers that flow signals from the valve, regardless of their directions, are taken as inputs, while the pressure signals are generated from the integration based on the continuity principle, equation 1.

$$\frac{dP}{dt} = \frac{\beta}{V}\left(\sum Q - \frac{dV}{dt}\right) \tag{1}$$

P- Pressure signal computed from the continuity principle
β- Hydraulic fluid bulk modulus
V- Cylinder chamber and connection pipe internal volume
Q- In and out flow of each cylinder chamber

In order to demonstrate how power transmission takes place between different domains, fig. 3 shows the mass component with its corresponding port. As can be seen, the mass component has as input the signal force from the cylinder component, and gives back the corresponding acceleration, velocity and position based on Newton's Law.

It is important to mention that attached to each icon, there can be one or more dynamic models with their respective equations, and parameters list, as described below.

Although very simple, with only eight state variables without considering motor dynamics, this example illustrates the complexity of modeling power transmission systems with signal port approach. Besides its natural representation that perfectly resembles the system functional model as usually known by the engineering community, multiport modeling brings other advantages over signal port, as seen below.

Because its background, signal port has been widely used to model control systems, where each sensor corresponds to a unique variable to be controlled, e.g. position, velocity, etc, however, if the model considers controller and plant, i.e. the system to be controlled that always involves power transfer, many difficulties arise. It is recognized that most of simulation systems do have pre-built blocks, that allow constructing a complete system from them. This feature avoids or diminishes the mathematical manipulation, and almost any need for coding. However, it is necessary a great deal of knowledge in order to represent the physical system with blocks, especially the understanding of causality among components. For example, why does the mass component have force as input and velocity as output, and not the contrary? Issues such as this can be simple to be understood by professionals with experience in dynamics, but the teaching experience has shown that they are quite complex to be explained to engineering students or even to engineers without background in dynamics.

As the system becomes larger, the following problems can occur with the use of signal port to model power transmission systems (Lebrun and Richards, 1997):

1. There will be an increasing number of connections between blocks.
2. There is a great chance of inadequate connections.
3. The resulting block diagram does not resemble the physical system.
4. Sometimes the necessary blocks do not exist in the pre-built library.

The first two problems can be partially solved by the ability to group smaller blocks into larger ones, creating supercomponents, while the last problem can be solved by the generation of the necessary blocks, which requires coding. However, due to its very nature, with signal port the third problem remains unsolved. Because such approach creates very complex diagrams to be interpreted even by experienced professionals and even a harder task to teach such concepts to engineering students. With multiport approach, functional blocks, i.e. components, are created based on their physical nature in terms of power transmission, representing the interaction through their ports via power variables, as presented in table 1.

Table 1- Power variables in different domains.

Energy domain	**Hydraulic, Pneumatic**	**Lin. Mech. /Rot. Mech.**	**Electrical**
e(t)- Effort variable	P- Pressure	F- Force / T- Torque	V- Voltage
f(t)- Flow variable	Q- Flow	v- Velocity / ω- Ang. Vel.	I- Electric Current

As can be noticed, the product of these variables gives power regardless of the energy domain. Thus, each component is modeled classified by the way it handles power, as described in table 2. The elements described in table 2 form the basis to understand power transmission, and the consequent physical behavior in technical systems. System causality is based on the adequate manipulation of these elements. From the analysis of these elements, it is noticed that all elements behave according to the integral causality, where the output is generated by the accumulation (integration) of the input variable (Auslander, 1974).

Table 2- Components classified in terms of power transmission (Karnopp et alli 1990).

Examples are presented in different energy domains, respectively: mechanical/ hydraulic-pneumatic/ electrical/ thermal
C- Capacitive Element- Spring and rotational stiffness/ volumetric chamber/ capacitor/ thermal capacitance
I- Inductive Element- Mass and rotational inertia/ flow mass transported in a pipe/inductor/ heat flow
R- Resistive Element- Viscous friction/ orifice or flow restriction/ resistor/ thermal resistance
TF- Transformer- this element transforms power between domains keeping a proportional relationship between the corresponding effort variables and flow variables. e_2=K.e_1; f_2= (1/K).f_1- Where, the indexes 1 and 2, represent input and output. For example, a hydraulic pump converts power, keeping a relationship between torque and pressure, rotational speed and flow.
GY- Gyrator- This element performs a similar operation to transformer. However, it gives a relationship between input effort and output flow variables. For example, in a solenoid there exists a relationship between its output force (effort variable) and its input current (flow variable).
0- Junction- This element is known as flow junction. It provides the law related to the sum of flow variables in a junction. For example, according to Kirchoff´s Law, in an electric circuit, the sum of all currents flowing in a node is equal to the sum of currents flowing out of it.
1- Junction- This element is known as effort junction. It provides the equation that all effort variables connected to the junction are properly divided among the elements connected to it. For example considering a shaft, the input torque is calculated by the sum of all output torque transmitted to the elements connected to the shaft and its bearings. The junction keeps that all elements connected to it will have the same flow variable, in the shaft example, all elements have the same rotational speed.
SE- Source of Effort- It provides specific effort variable to the system, it can be constant or any other function, regardless of the flow demand from it. For example, in an electric circuit, a voltage source provides constant voltage regardless of the current demand from it.
SF- Source of Flow- It represents an element giving a specific flow variable regardless of the effort demanded from it. For example, in a hydraulic system, a hydrostatic pump is usually modeled as a flow source, because it provides flow independently from the output pressure (effort variable).

From the above discussion, there are clear advantages in using multiport approach to teach modeling of multi-domain power transmission systems. However, the use of elements in the direct form as presented in table 2 brings other problems as discussed in (Lebrun and Richards, 1997). Especially, because such terminology is not widely spread in the engineering community, even among domain experts. For example, the author faced such reality during the interaction with different professionals to develop an expert system for hydraulic system design, as presented in (Silva, 1998). In order to demonstrate the teaching of some of the concepts mentioned above in a manageable manner, the next section introduces the system AMESim.

3. AMESim brief description.

The author has used AMESim as an environment to teach dynamic modeling and simulation in the last five years. This experience has embraced both industrial and academic sectors. In academia, most of the experience has been in a modeling and simulation course at UFSC offered to engineering students, mostly post-graduate but also with participation of undergraduate students. In industry, the experience has been related to courses on hydraulic systems at EMBRAER/PEE/ITA, electric drivers and electro-mechanical systems at WEG Motors, and hydraulic systems/components and fuel injection systems at BOSCH.

The author is also the coordinator of a R&D project, involving expert systems and dynamic modeling/simulation using AMESim for natural gas networks. The project, known as SEGRED, has as partners Petrobras and TBG- Bolivia-Brazil Natural Gas Transportation Company.

As can be inferred from this experience, the author has used different AMESim features. Because of the limitation here, only some key AMESim functions are presented. In order to understand the breadth of this virtual environment, it is relevant to analyze its modular structure. AMESim is a virtual environment composed of a set of computational tools to create, analyze, exchange and customize dynamic models with a support of a set of libraries. These libraries embrace models from different domains, such as hydraulic, pneumatic, mechanical, signal, and so on, but also libraries with models generated from a combination of libraries, providing more complex models, such are the cases of powertrain and electro-mechanical libraries (Imagine, 2005). In order to give a better view of the system modules, table 3 presents a brief description of its modules.

Table 3- AMESim modules with its corresponding functions (Imagine, 2005)

AMESim	Create new models, modify diagram of a previous model, change submodel of related to a component, load complete models, change parameters, set-up batch runs, perform standard or batch runs, plot results, perform linear analysis.
AMECustom	With this module, it is possible to customize a previous model. A customized object is based on a generic model on which a mask is put over, allowing access to only few parameters. This module permits the exchange of models between different companies hiding confidential aspects of the model.
AMERun	This is a run-only version of AMESim, i.e. it provides only few functions, e.g. load complete models, change parameters, set-up batch runs, perform standard or batch runs, plot results, perform linear analysis. This module is useful in case an engineering department that deals with model creation, passes its models to other divisions for analysis under different conditions.
AMESet	This is a module for more-advanced users, it allows the creation of new models and libraries based on coding equations in C language in a comprehensive user interface.

As mentioned before, although very powerful as theoretical back grounded, the use of bond graph terminology to represent engineering systems brings several problems due to the complexity of the power diagrams. A study including bond graph diagrams with corresponding AMESim models is presented in (Hayat et alli 2003). Therefore, in order to take advantage of bond graph technique, without the need of dealing with its complex power flow representation, AMESim provides a user-friendly interface to build and analyze multi-domain systems, as shown in fig. 4.

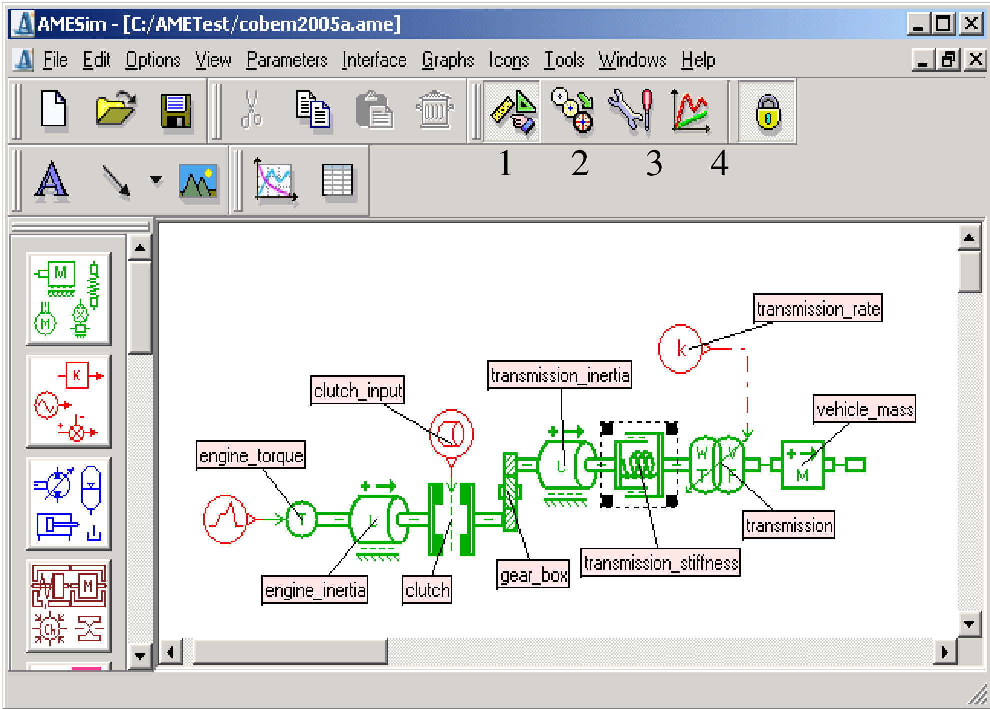


Figure 4- Transmission model and AMESim interface.

Figure 4 introduces AMESim interface and presents a power transmission system model. The numbers in the upper part of the figure represent different modes defined in order to built and simulate a model, as described in table 4.

Table 4- Mode Description

1- Sketch	Build the system diagram based on icons from existing or user defined libraries.
2- Submodel	Define the adequate model for each icon, since attached to each icon it is possible to have more than one engineering model. Here, the user should analyze the different implications of modeling hypotheses. There are premier models to speed up the process that can be used as default options.
3- Parameter	Define the parameters for every submodel. The system also presents default parameters.
4- Simulation	Define simulation parameters, i.e. time, error tolerance, standard or batch simulation, etc, perform the simulation and analyze the results from graphs.

The model shown in fig. 4 has the following components, from the mechanical library: rotational inertia, rotational stiffness, torque source (representing engine torque), mass and transmission. Signal and data table inputs from the signal library. Each library is distinguished by a specific color, the libraries are placed on the left side of fig. 4, and are available only in the sketch mode. With this representation, the attention focuses on the dynamic behavior of the transmission, including engine and transmission inertias influence on the car movement.

As previously described, the modeling task in AMESim is strongly connected to the physical understanding of the phenomenon, while the mathematical manipulation is hidden from the user, though it is available to be analyzed. The decomposition of the modeling/simulation process in four modes, as presented in table 4, brings another advantage for teaching, because it allows creating relatively complex systems, in a manageable manner, evolving the modeling complexity in a same sketch. In order to exemplify this process, consider a simple gear model, figures 5a and 5b. This model is placed in the powertrain library as an icon that resembles a familiar component. Attached to this icon there are four levels of modeling that can be selected in the submodel mode (Imagine, 2004):

- Level 0 corresponds to the simple gear regime (mainly the transformer).
- Level 1 introduces losses by constant efficiency and introduction of a measure table of efficiency losses as a function of the rotation speed and the load. The parameters of these files depend on the temperature of the gearbox oil and the average oil level.
- Level 2: complete planetary geartrain only: The inertias of pinions are taken into account without teeth backlash.
- Level 3 introduces extra dynamics since it permits the observation of the effect of tooth stiffness as well as the clearance between the teeth. The shock of the teeth is modeled and facilitates the analysis of vibrations produced on drivelines.

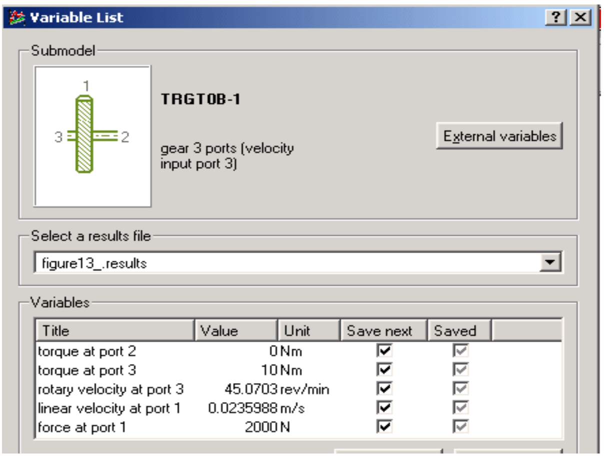


Figure 5a- Gear model with parameter list.

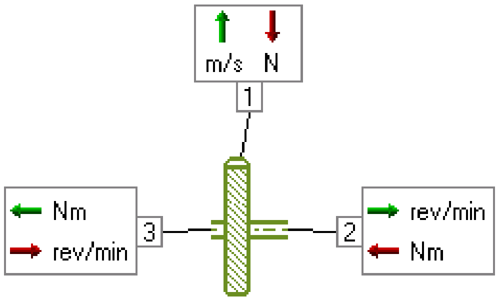
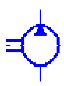
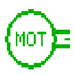
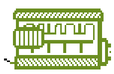
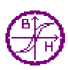


Figure 5b- Gear model with its ports.

Figure 5a shows the list of parameters related to a gear model. As can be seen, the parameters are defined with their ports. While fig. 5b presents the details of each port in terms of their power variables definition, as table 1. By selecting the variable on the above list, the user can analyze its behavior through the simulation. The same approach of different models attached to a unique icon is carried out for different components. The next table presents some examples from different domains.

Table 5- Some model icons and their possible submodels.

	• Ideal fixed displacement hydraulic pump • Hydraulic pump with volumetric and mechanical efficiency • Hydraulic pump with oscillations
	• Constant speed prime mover • Prime mover with speed varying linearly with torque
	• Engine torque as a copy of the input signal • Engine torque defined by ASCII file T=F(ω, θ) • Engine torque limited to a maximum value = f(engine speed) • Engine torque defined by two ASCII files (engine velocity and harmonics)
	• vehicle load (wheels included) • vehicle load (wheels included) with C_x air penetration coefficient
	• magnetic material property defined by coefficients • magnetic material property defined by a table.

Note: the magnetic property element, similar to fluid property, thermal solid property, and gas data, has no ports, rather these elements identify the corresponding properties and related to components in the sketch via specific index. Thus in a same sketch, it is possible to have different materials as means of power transmission.

As can be concluded from table 5, the teaching of dynamics can be adapted to the students' level depending on the level of complexity that is being considered, thus it is possible to create representative models allowing some conclusions, and emphasizing the hypotheses inherent of each model.

Modeling is above all a task of making simplification, based on the understanding of the underlining physical principles and analyzing the impact of these simplifications in the simulation results. Therefore while it is not correct to neglect key aspects, it is also wrong to include all variables involved in the phenomenon without studying their true impact on the dynamic behavior, with such practice the model can easily become unfeasible to study or even too time-consuming to simulate. Thus the challenge in modeling is to have a trade-off between a great deal of simplification that losses value and too many variables that take the attention from key aspects and brings unnecessary complexity.

In order to achieve such trade-off, different methods have been developed, one of them is known as MORA- Model Order Reduction Algorithm. The method is based on the activity and activity index (Hayat et alli 2003). The activity of an element is defined as a temporal integration of the power absolute value, and its activity index is the ratio between its activity and the total system activity, as described in equations 2 and 3.

$$Ai = \int_0^t \left| e(t).f(t) \right| .dt \tag{2}$$

$$IAi = \frac{Ai}{\sum Ai} \tag{3}$$

Where: *Ai*- Element i Activity; *IAi*- Element i Activity Index;
e(t) and *f(t)* are effort and flow variables, as defined in table 1.

As presented before, the computation of flow and effort variables is intrinsic in AMESim simulation, thus besides its state variables, attached to each element there is a determination of its activity index.

After simulation, all elements are ranked according to this variable in order to provide guidelines on model simplification with the elimination of "least active" elements, i.e. those with the lowest activity indexes. In this process, elimination means the change of a higher order model by a lower order one keeping the component in the system. For example, for the model presented in fig. 4, simulation can provide results as figures 6 and 7.

As can be seen in fig. 6, the components are ranked according to their activity indexes in a ascending order, the list also includes the element category, i.e. C- Capacitive, I- Inertial, R-Resistive, according to table 2. Here, again, the emphasis is on the model physics, and component categories.

From the analysis of the activity index list, it can be concluded that the dissipative elements related to both inertias (engine and transmission) have very small activity indexes, such conclusion can provide a guideline to use simpler submodels for these components. For those interested in this method, a comprehensive study of this application in order to simplify a model for powertrain evaluation with experimental validation is presented in (Hayat et alli 2003).

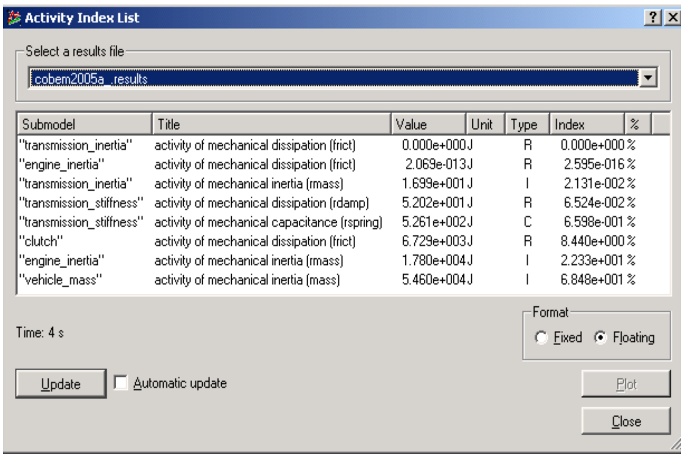


Figure 6- Activity index list.

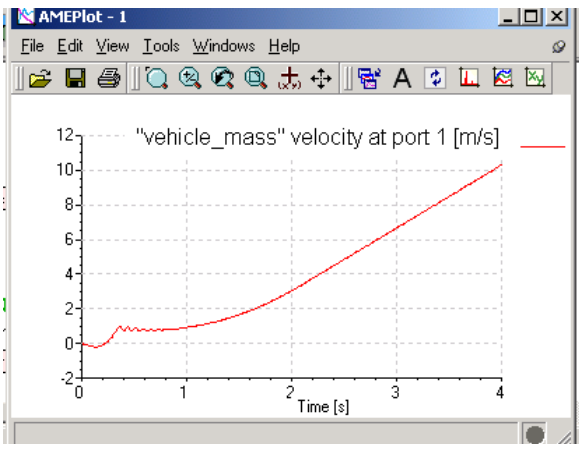


Figure 7- Vehicle velocity.

The results, presented in fig. 7, identify the vehicle behavior considering at start the following conditions:

- The car is at rest but on a 10-degree slope (upwards).
- The engine speed is initially 2500 rpm and there is a constant torque of 200 Nm.
- The clutch is disengaged for 0.1 s (input signal 0) then ramped to fully engaged (input signal 1) in 0.25 s.

The transmission model, presented in fig. 4, is quite simple with only five state variables, its corresponding signal. However, its flow diagram can prove to be rather complex. Moreover, with AMESim graphical representation, the underlining physics, i.e. power transfer through components is emphasized.

4. Conclusion

The paper presents a comparison between signal port and multiport techniques, emphasizing the advantages of using multiport for teaching and modeling multi-domain systems. It also introduces the main features of AMESim, an environment to support dynamic modeling of multi-domain systems for industrial and academic activities as well. Its main advantages are concentrated on the physical definition of all elements, based on their causality and power transfer relations, very powerful user interface, and strong numerical capabilities. In teaching, the advantages of applying AMESim can be summarized as:

- Better understanding of causality and power exchange among components;
- Ease integration of components from different energy domains;
- Adaptation of teaching according to the students' background, due to reduction or amplification of model complexity, keeping the same system diagram;
- Emphasis on the physical understanding of power transfer;
- Simplification of simulation models compared to typical signal flow diagrams, thus allowing higher order models manipulation.

AMESim also contains more advanced functions such as Frequency Analysis, Design of Experiment and Optimization to support dynamic modeling. Based on the author's experience, the environment is of great use on teaching dynamics in different energy domains.

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