Innovative Hybrid Modeling Approach to Enhance Green Design based on Fully Integrated Mechatronic System Simulation

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Abstract: Current economic and environmental constraints are pushing OEMs and system integrators to design high performance systems with tighter development time requirements. They naturally resort to simulations to avoid the time and cost of early prototyping. This establishes a new "language" of virtual machines and components that hydraulic, electrohydraulic and control component manufacturers also need to acquire to be able to market their products.

This paper presents an innovative hybrid modeling methodology to aid the design and analysis through simulation of complete electrohydraulic and mechatronic systems and machines. This methodology combines modeling using physical parameters and equations, and modeling using multidimensional high-level performance curves. All of the above embedded into compatible and interchangeable gray boxes that can be used and customized according to the machine performance simulation needs.

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1. INTRODUCTION

The simulation of component behaviors and characteristics has been shown to bring significant value to companies by reducing the risk and effort in prototyping systems. In spite of these advantages, the idea of simulating components and systems is not yet as widespread as it could potentially be. Moreover, in the cases where simulations are used, they are usually restricted to specific phenomena where only few behaviors are examined in detail.

With the accelerating advances in computing technology, this limitation is definitely not due to any issues with hardware or software capabilities. It is rather due to the challenge of having to spend great deals of effort in establishing simulation models and frameworks, because of a lack of structured and widespread easy to use simulation frameworks. Indeed, although simulation tools are ubiquitous, establishing a simulation model for a component has to be done from scratch, which makes it difficult to adapt or reuse in different settings. Developing simulation models becomes restricted to a select few, and studies tend to focus on a specific, isolated subsystem or technology, rather than on the integration of multiple technologies within a global system.

In order to counter those difficulties, the user's focus must be taken away from the challenges – mathematical, physical, numerical modeling and related software implementations – and steered towards the understanding of energy flow within the whole system being studied. In order to do that, general simulation formalisms become too generic and a more accessible, approach must be introduced. Such an approach would combine the benefits of advanced mathematical and physical representations, and of common-knowledge representation of component behaviors like input-output tables, or graphical representation.

In this article, we present a novel electrohydraulic and mechatronic simulation approach that is suited to the majority of today's industrial simulation needs. The hybrid approach, explained in section 2, allows the user to tune, assemble and imbricate elementary pre-configured modules according to easily simulate systems that potentially involve a high number of precisely modelled components, without losing the flexibility or adaptability.

In section 3, modelling of different components – thermal engine, piston pumps and motors, proportional valves and other actuators – will be explored, and real manufacturer components will be modelled using hybrid simulation models. In section 4, two real-time operator-controlled simulation examples focusing on energy efficiency will be presented: an electrohydraulic mobile machine involving a load-lifting mechanism, and an automatic transmission control system. Simulation results are shown to illustrate the capabilities of the hybrid approach in improving energy consumption characteristics and development costs of industrial machines. We conclude in section 5 with general remarks about the method's key characteristics as well as some remaining challenges.

2. MODELLING VIRTUAL COMPONENTS & SYSTEMS

The purpose in this section is not to summarize or recreate simulation formalisms and theories but rather to simply bring together existing approaches to make the simulation world easily relate and adapt to real world practical needs.

With the current widespread energy-saving trends, most of today's practical needs involve the study of power transmission chains and the focus on the efficiency of each element in those chains, whether they be electrical, hydraulic, pneumatic or mechanical.

SIMULATION SCOPES – Establishing the simulation scope is crucial when designing a virtual model. Once the simulation scope is established, it becomes more straightforward to understand the different hierarchical levels needed to paint a complete and useful picture of the system being studied. The following list shows different scopes that can be focused on:

1. Complete multi-technology machine;
2. Technological System;
3. Function;
4. Component;
5. Subcomponent and/or physical object.

The different scopes are illustrated in Fig. 1 and Fig. 2, where a complete simulated machine is presented with all its different models.

Complete Machines and Technological Systems – Building a system using several technologies involves many fields of expertise. The idea of simulating complex multi-technology systems or complete machines was a serious challenge only a few years back and was generally unachievable by most machine designers. As machines become more complex and intelligent, there are definite advantages in building a complete virtual system and in providing a global solution involving different fields of expertise providing transfer of knowledge, the ease of access to technical information, and the availability of smart design canvases. This all cannot be done using static CAD drawings.

Functions and Components – Recently, the market demand for simulating functions has grown considerably. This approach has the benefit of offering quick and affordable solutions for OEMs, system integrators, and component manufacturers. Engineering, prototyping and validation time is reduced. As manufacturers are displaying themselves more and more as solution providers, they are offering more and more functional solutions: power steering, braking, power units, etc.

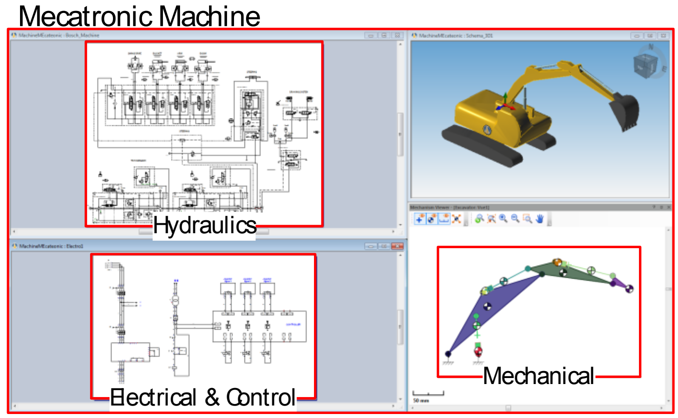


Fig. 1: Complete Multi-technology Machine Simulation

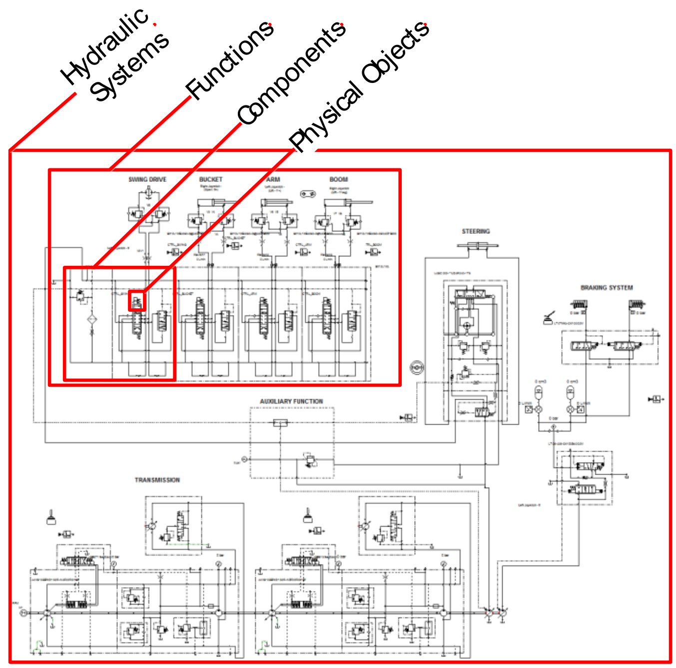


Fig. 2: Different Levels of Simulation Scope

In spite of the widespread approach of providing functional solutions, simulating individual components still has advantages and provides valuable information as to specific constraints or abilities a given component might have in a given environment. Moreover, building a functional model must begin with integrating individual components. In general, a higher-level simulation scope will be based upon the integration of different modules from a lower level.

Subcomponent and physical objects – Going one level deeper in the modeling of a component will lead to physical modeling. Indeed, the building blocks of a component model would be the physical equations which themselves involve one or more areas of physics:

mechanics, fluid mechanics, electricity, magnetism, thermodynamics, etc. This level of modeling, mainly useful for component manufacturers, also has its challenges; many companies would either have to invest in R&D departments or resort to outsource these kinds of studies to specialized contractors.

ADAPTED MODELING APPROACH – In the concept of system simulation, there are two abstraction levels that can be considered, and a wide spectrum of intermediate specificity abstraction levels in between. The first level which falls at the acutely specific end of the spectrum is the lumping of all the phenomena involved in the system within a single all-encompassing transfer-function type of representation that takes a set of input stimuli and converts it into predetermined outputs. This approach is specific to the system being studied and is practically unadaptable when a system is slightly modified. At the most generic end of the spectrum, high-level representations of system dynamics can follow a generic language like the one introduced by B. Zeigler B. in “Theory of Modeling and Simulation“ [10]. This representation is indeed general and can be adapted to practically any type of simulated systems. However, because it is very general, it is often out of reach with the practical needs of the user and is thus challenging to use without translating it into a more relatable format.

The hybrid modeling approach we propose in this paper aims to establish a middle ground where enough generality and specificity are traded to get a unified, scalable abstraction level that can represent simulation models from any of the aforementioned scopes using a common vocabulary that is easily relatable. It is basically a way of organizing the different levels of simulation scopes in an easily adaptable architecture. A way to do this is by regarding the systems as power transmission chains. This assumption is easily justifiable because in most practical applications, the purpose of the system is to drive a set of given actuators from a given source. Hence, the global simulation formalism we propose can be represented as shown in Fig. 3, and its adaptation to power transmission systems in Fig. 4, such as explained by V. Rémillard in “New Software Generation for Greener Energy Efficient Mechatronic System Design & Analysis“ [8].

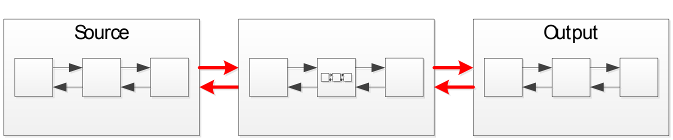


Fig. 3: Global Simulation Formalism

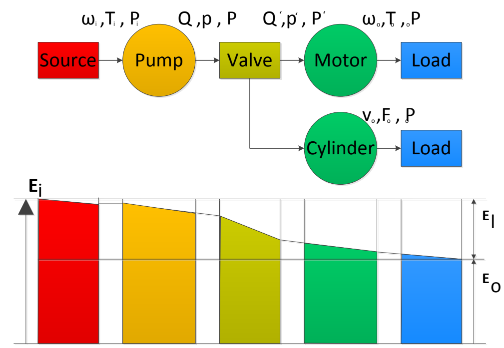


Fig. 4: Power System Simulation Formalism

HYBRID SIMULATION MODEL TYPES – Each entity in the chain can be viewed as a box where the inner workings as well as the inputs and outputs are embedded. The system integration is done by simply daisy chaining those elements. The link between an element and the adjacent ones represent a certain type of power transfer.

The choice of the embedded model will depend on the level of detail required and on the information available. When enough simplification is allowed, some internal elements may be modeled as simple data maps while others are modeled with their dynamics.

Fig. 5 shows this concept of “Gray Box” where a simulation model is a mix of known dynamic and static models and of unknown functions represented as high-level data input-output maps. These inner entities exchange information among each-other and with the outside environment.

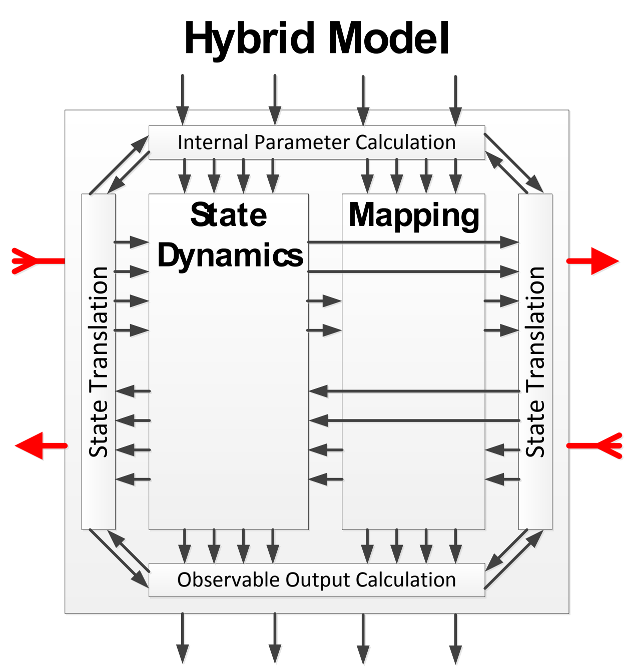


Fig. 5: Elementary Gray Box Model Concept

State Dynamics – The dynamic part of the model is considered mathematically as smooth and can be represented by differential equations.

Data Mapping – For more complex phenomena, it is sometimes difficult to determine all the exact relationships, especially when valuable information is missing, like internal component geometry, or proprietary manufacturer data. Also in some cases it can be counterproductive to model all the low-level interactions that give a simple high-level global behavior. In these instances, it can be useful to use customizable tables or curves that represent the global input-output maps. The advantage of using this approach is that it can be simpler to gather input-output data from a physical component rather than design complex probing and calculation tests.

Data Exchange – The integration of sub-models using inner and outer data exchange paths is also shown in Fig. 5. The vertical arrows represent the inputting of parameters and the probing of internal states by the user. The bold horizontal arrows represent the main power variables that are exchanged with adjacent blocks. Some translation processes may be necessary to precondition some parameter inputs or to calculate user understandable outputs from the internal states or parameters.

It is this inner organization, combined with the ability to nest blocks within each-other that give the approach its significance. Whenever information about the system is lacking, simplified models can be used within a block. When more precision is required, the same block can be remodeled with more advanced dynamics without having to readapt other blocks.

MODELING VIRTUAL MACHINES: ENHANCED PROCESS – When creating a simulation model, the user may follow one of two approaches: Upstream or Downstream.

Upstream Design – It consists of programming the inner dynamics and equations of a component. It may ultimately provide flexible modules for the user but can be challenging to integrate in a global process. It usually requires solid understanding of programming principles and languages.

Downstream Design – In order to be efficient in the study of virtual systems, having to spend the time to program all models from scratch, as well as to integrate those models in a coherent global behavior becomes a big challenge that can quickly render the simulation stage impractical. This process leads to prototyping phases which, when undertaken too early in the lifecycle of a product, is synonymous to high cost and difficulty of adaptation. It becomes advantageous to be able to use a common language to prepackage models that can be reused in a modular way.

Fig. 6 illustrates an ideal context of machine design, where the hybrid modelling approach is presented in an integrated working process. The presented Downstream design approach consists of integrating those hybrid pre-programmed blocks right away in higher-level systems such as explained in [8]. Using performance curves make customization on these components straightforward to quickly and efficiently improve global characteristics of a machine. It makes the simulation of multi-component systems more accessible, but will greatly depend on having a complete set of Upstream-built components.

From Fig. 6, this simply means having libraries or catalogs of parts and functions (1) from different technologies that are compatible with each-other. The modeling effort would then be already done for one component, function or system, and would be easily readapted and integrated (1') in different systems (2) and ultimately complete machines (3) using data mapping, with minimum effort from different users.

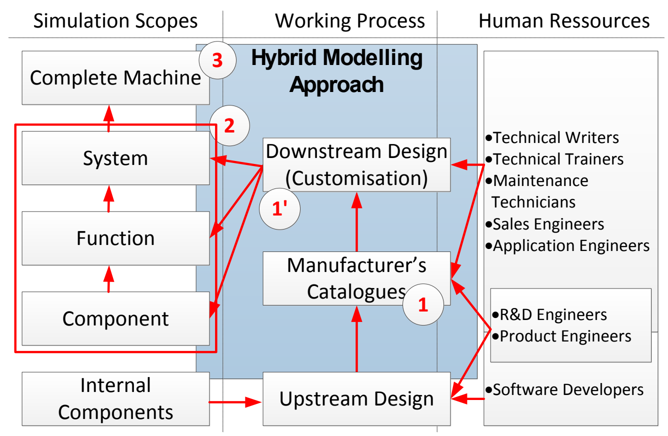


Fig. 6: Hybrid Approach Integration in Working Process

3. HYBRID SIMULATION MODELS

In this section, different simulation models will be explored and defined using the hybrid approach developed in the previous section. Similarly to the approach introduced in [8], the models will be developed to focus on the energy transfer and multi-technology aspects. The dynamic differential equations as well as the data mapping sections will be emphasized.

THERMAL ENGINE – Developing the complete model of a thermal engine involves thermodynamic relationships. The development of the fundamental equations is not subject of this article. However, because the model is essential to analyse power transmission systems, the model will be presented in the form of data maps.

Data Mapping – The manufacturer's specifications of a thermal engine present graphical relationships between the rotation speed and the torque generated by the engine. These curves represent effective power of the motor at different nominal speeds, as shown in Fig. 7.

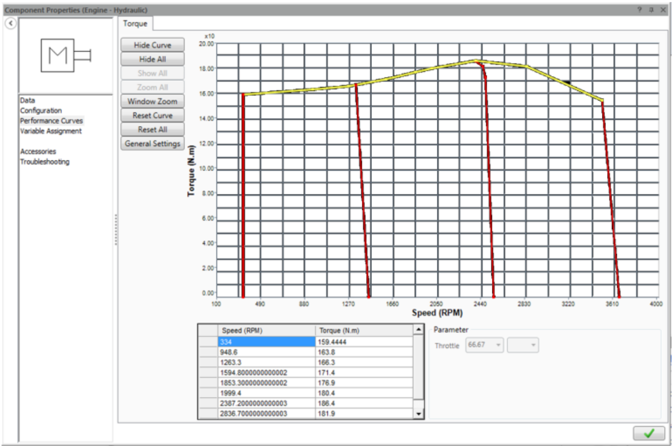


Fig. 7: Power Curves of a Thermal Engine

In addition, the stalling behavior of the engine can also be represented by these same curves: if the torque applied is higher than a certain level, the maximum power envelope will dictate a stalling behavior. Note also that manufacturers extend these specification curves to fuel consumption, so it can be also be mapped in simulation to compute energy of a complete machine duty cycle.

HYDRAULICS – In this section, hybrid models of components that are involved in hydraulic power transfer applications will be developed.

Pumps and Motors (Transmission) – Because pumps and motors have many theoretical similarities, their models will be developed together.

Fundamental Equations – A pump receives mechanical power P_i and transforms it into hydraulic power. The output hydraulic power is described by:

$$P = Q \cdot \Delta p \qquad (3.1)$$

Where Q is the output flow and Δp is the differential pressure between the inlet and the outlet of the pump.

As for the motor, it receives hydraulic power and converts it into mechanical power P_0 , as per:

$$P_o = \omega_o \cdot T_o \qquad (3.2)$$

Other fundamental equations will also be developed such as in [2] and [9]. For any hydraulic system that has both an input and an output flow, the continuity principle dictates:

$$\rho(Q_i - Q_o) = \frac{d}{dt}(\rho V) \qquad (3.3)$$

If we consider the compressibility modulus β of a fluid with specific mass ρ_0 at a given state, the current specific mass is given for another fluid state by:

$$\rho = \rho_0 \left[1 + \frac{1}{\beta}\Delta p - \alpha \Delta T \right] \qquad (3.4)$$

By considering isothermal compressibility, the compressibility modulus is defined by

$$\frac{1}{\beta} = \frac{1}{\beta_0}\left(\frac{d\rho}{dp}\right)_T = -\frac{1}{V}\frac{dV}{dp} \qquad (3.5)$$

And the equivalent compressibility modulus is defined by combining many effects: β_l for the fluid compressibility, β_c for volume changes in pipes, β_g for the compressibility due to the presence of gas in the fluid:

$$\frac{1}{\beta_e} = \frac{1}{\beta_l} + \frac{1}{\beta_c} + \frac{V_g}{V_t}\frac{1}{\beta_g} \qquad (3.6)$$

From equation 3.3 to 3.5, the continuity equation for a pump and a motor is given by

$$Q_i - Q_o = \frac{dV}{dt} + \frac{V}{\beta}\frac{dp}{dt} \qquad (3.7)$$

From previous equation, the relationship can be further developed by including leakage in the model define by Labonville in “Conception des circuits Hydrauliques; une approche énergétique” [1]. If we consider volume change rates:

$$\frac{dV_1}{dt} = -D_P \omega_i \qquad (3.8)$$

$$\frac{dV_2}{dt} = +D_P \omega_i \qquad (3.9)$$

Where D_p and ω_i represent the displacement of the pump and its input rotation speed.

As explained in [8], we see that efficiency of the pump is a function of many parameters that are difficult to obtain, such as the internal and external leakage coefficients c_i and c_e. This is why a hybrid model needs to be defined to analyze its integration in the energy transmission loop.

Relations 3.10 and 3.11 are obtained.

$$\underbrace{Q_1 = D_p\omega_i - \frac{V_1}{\beta_e}\frac{dp_1}{dt}}_{Dynamics} \underbrace{-\left[c_i(p_1 - p_2) + c_e p_1\right]}_{Mapping} \quad (3.10)$$

$$\underbrace{Q_2 = D_p\omega_i - \frac{V_2}{\beta_e}\frac{dp_2}{dt}}_{Dynamics} \underbrace{-c_i(p_1 - p_2) + c_e p_2}_{Mapping} \quad (3.11)$$

A similar analysis can be done for hydraulic motors.

$$\frac{dV_1}{dt} = +D_m\omega_o \quad (3.12)$$

$$\frac{dV_2}{dt} = -D_m\omega_o \quad (3.13)$$

Where D_m and ω_o represent the displacement of the motor and its output rotation speed.

Which yields the following hybrid model for a motor:

$$\underbrace{Q_1 = D_m\omega_o + \frac{V_1}{\beta_e}\frac{dp_1}{dt}}_{Dynamics} \underbrace{+\left[c_i(p_1 - p_2) + c_e p_1\right]}_{Mapping} \quad (3.14)$$

$$\underbrace{Q_2 = D_m\omega_o - \frac{V_2}{\beta_e}\frac{dp_2}{dt}}_{Dynamics} \underbrace{-c_i(p_1 - p_2) + c_e p_2}_{Mapping} \quad (3.15)$$

A similar analysis can also be performed to model a cylinder using a hybrid model.

Data Mapping – For the data mapping part of the hybrid model, we need to include efficiency considerations for the pump and the motor as a function of several other parameters. In order to have an accurate pump and motor models for all operating points, we need to be able to define a 5 dimension efficiency model, both volumetric and mechanical, such as in the following relationships:

$$\eta_{op} = f(D_p, \Delta p, \omega_i, \mu) \quad (3.16)$$

$$\eta_{om} = f(D_m, \Delta p, \omega_o, \mu) \quad (3.17)$$

Graphically, the previous relationships can be represented as shown in Fig. 8.

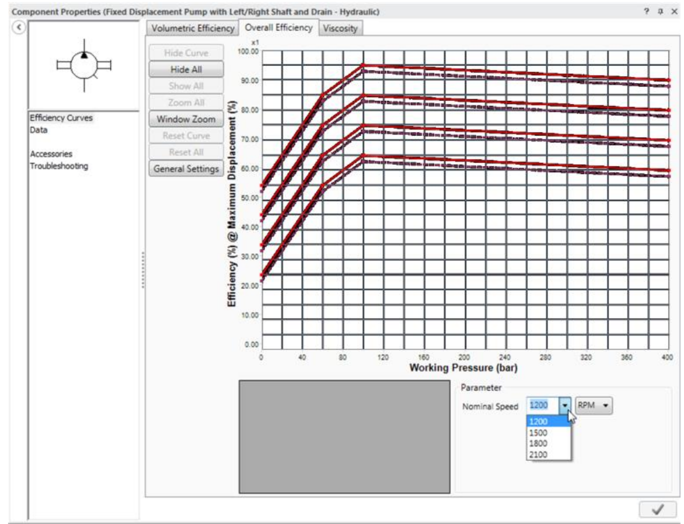


Fig. 8: Pump Efficiency Mapping

Compared to the model developed in [8], the pump efficiency is adjusted for various viscosities, such as in Fig. 9.

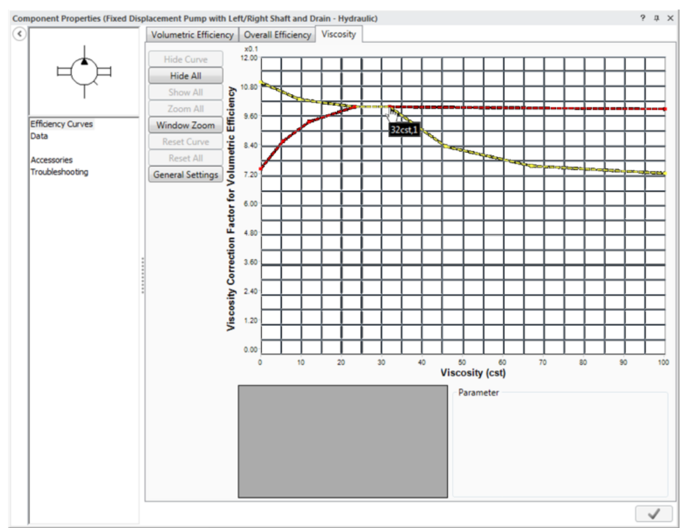


Fig. 9: Viscosity Correction Factor

Valve Motion, Flow Gain & Pressure Drops - In this section, fundamental equations of components that modulate hydraulic energy will be explored.

Fundamental Equations – To start the analysis, we start by establishing a relationship that dictates the motion of the moving part of a proportional valve. It can be represented by a second order differential equation with position x and its time derivative. With parameters mass m, damping coefficient c and spring stiffness k, the relationship is defined by

$$F = m\ddot{x} + c\dot{x} + kx \quad (3.18)$$

Also, flow Q and differential pressure Δp are a function of the position of the valve. There are two general models to define theoretical pressure drops. The one to select depends on the geometry of the flow path.

If we describe the flow path with an orifice model, we use the following equation:

$$Q = C_d A_o(x)\sqrt{\frac{2\Delta p}{\rho}} \qquad (3.19)$$

Where C_d is the discharge coefficient, ρ is the specific mass of the fluid and $A_o(x)$ is the area aperture function with respect to position x.

If the flow path is a pressure line model, such as the Darcy-Weisbach [7] relationship, we can use:

$$\Delta p = f\,\frac{L}{d_i(x)}\,\frac{\rho (v_f)^2}{2} \qquad (3.20)$$

Where f is the flow loss coefficient, that can be established using a Moody chart or other methods [7], L is the length of the line, ρ is the specific mass of the fluid, v_f is the fluid velocity and $d_i(x)$ is the diameter as a function of position x.

Data Mapping – Equations 3.19 and 3.20 can be presented using curves such as illustrated in Fig. 10. We see the aperture $A_o(x)$ as a function of valve's stroke, where the appropriate geometrical model can be selected as needed.

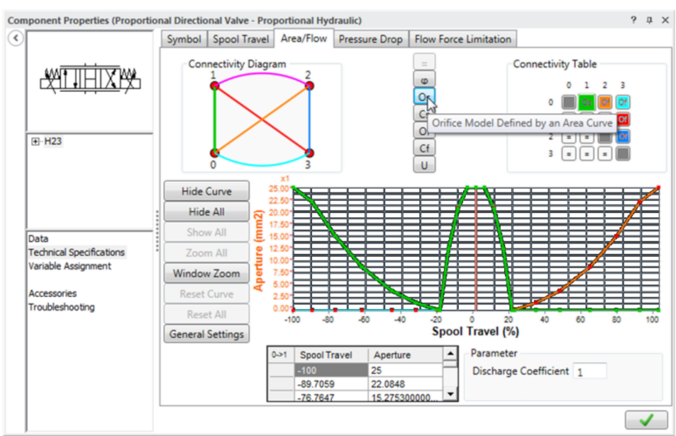


Fig. 10: Orifice Model using Curves

However, once again, the real geometry of a valve cannot be usually represented completely or precisely using any one of these theoretical models.

Data mapping makes it possible to define a hybrid model of the flow characteristics of the valve directly with the appropriate flow gain curve, such as in Fig. 11.

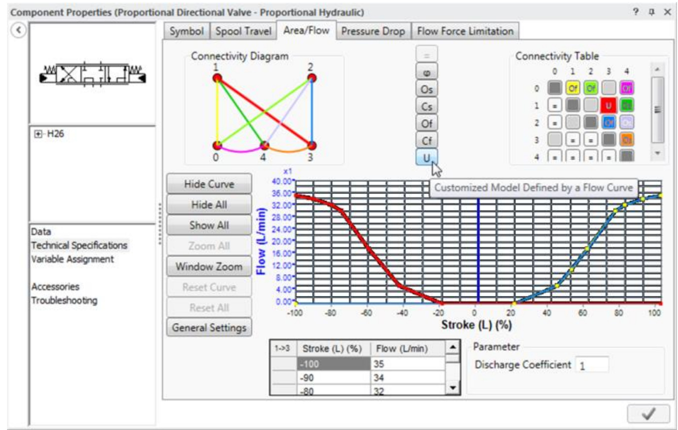


Fig. 11: Flow Model Curves (Eaton CML60)

Moreover, data mapping includes considerations of more complex phenomena, such as hysteresis and flow force effects by defining two extra curves. The curve in Fig. 12 adjusts the displacement characteristics and the one in Fig. 13 adjusts the flow relationship by emulating the closing/opening behaviours of the valve as a function of the flow force due to increasing Δp.

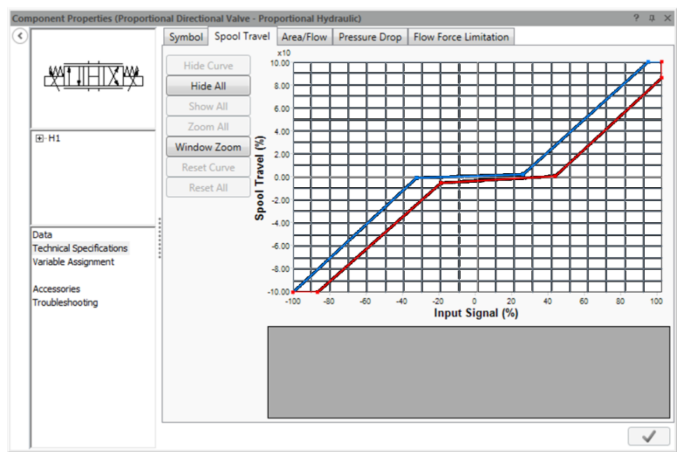


Fig. 12: Hysteresis Curves

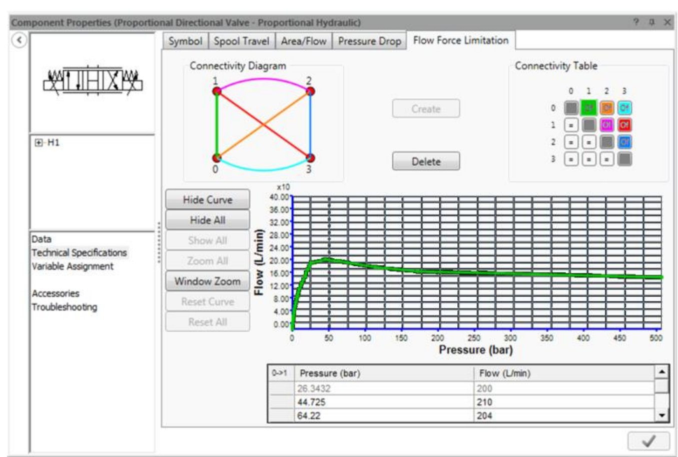


Fig. 13: Flow Force Curves

MECHANICS – Finally, the power transmission chain is terminated by load characteristics of a mechanical object to be moved. Since it is the primary objective to adapt the design of the whole transmission to the mechanical load and according to desired performance criteria, the analysis would not be complete without realistic simulation models of load profiles.

Mainly, two load profiles will be established. One will be developed according to the rigid body theory, rather associated with the hydraulics cylinder motions, and the other will be a torque model brought back to the hydraulic motor shaft.

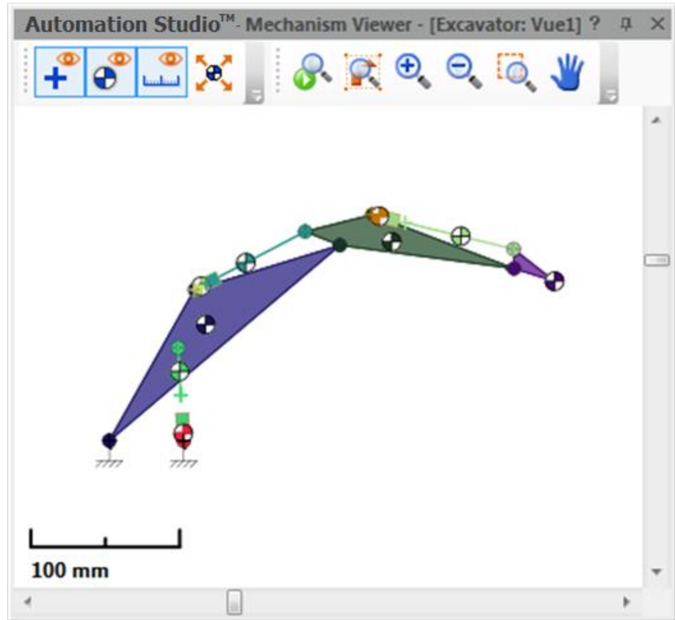
<u>Rigid Bodies</u> – The rigid body dynamics can easily be described by a system of differential equations describing the dynamics of individual bodies in kinematic relations each other. So this model will mainly be described using fundamental equations, where energy loss parameters can be added using constant values.

Fundamental Equations – As explained by R. Featherstone in "Rigid Body Dynamics Algorithms" [4], the following relation between joint accelerations $\ddot{q}$ and forces τ applied on the bodies of the mechanical system is used:

$$\tau = M\ddot{q} + C(q,\dot{q}) \quad (3.21)$$

Where M is the generalized inertia matrix, C is the generalized bias force depending on q - the joint coordinates - and $\dot{q}$ - the joint velocities. This equation can be efficiently computed using such as algorithm in [4].

Interaction with the hydraulic simulation is done in two directions: forward dynamics, where the hydraulics simulation provides forces/torques and the mechanical simulation computes linear/angular accelerations, and inverse dynamics. An example of a rigid body mechanism is shown in Fig. 14.



<u>Fig. 14: Example of a Rigid Body Mechanism</u>

Data Mapping – The mechanical system can also store energy in the form of kinetic energy when it is moving, gravitation potential energy when masses are lifted, and elastic potential energy when springs are compressed or other bodies bent.

Power losses proper to the mechanical system are mainly due to friction in the joint motion that can be simplified using coefficients. Taking all these coefficients into account and multiplying them by the corresponding joint velocity modifies the generalized bias force $C(q,\ddot{q})$, which becomes a non-conservative force. The actuator force used to fight this friction is not all used to accelerate the mechanism; therefore the output power is smaller than input power:

$$P_{in} = \tau_{in} \cdot q_{in} \geq P_{out} = \tau_{out} \cdot \dot{q}_{out} \quad (3.22)$$

This approach makes power transfer and efficiency analysis considerably more practical, because the individual parameters are easy to relate to by the designer, as opposed to when considering a generic approach to the complete mechanical system.

<u>Torque Model</u> – There are several combined effects that produce a resulting torque on hydraulic motors. Some of them will be considered in our model using fundamental equations.

Fundamental Equations –The output torque of a motor can be described using the following mechanical relation:

$$T_o = J\alpha + T_L + \sum T_f \quad (3.23)$$

And if we consider hydraulic relationships for this motor, we can rewrite 3.23 as follow:

$$T_o = (p_1 - p_2)D_m\eta_{mm} = (J_m + J_L)\ddot{\theta} + B_L\dot{\theta} + T_L \quad 3.24)$$

And if we add a reduced/multiplied speed ω_r of ratio N, an efficiency μ_{red}, such as

$$N = \frac{\theta_0}{\theta_r} = \frac{\omega_0}{\omega_r} = \frac{\alpha_0}{\alpha_r} = \frac{T_r}{T_0}\frac{1}{\eta_{red}} \quad (3.25)$$

The resulting torque is defined by

$$T_r = J\alpha_r + b\omega_r + T = \frac{J\alpha_0}{N} + \frac{b\omega_0}{N} + T \quad (3.26)$$

$$\begin{aligned}\eta_{mm}T_m &= J_m\alpha_0 + T_0 = J_m\alpha_0 + \frac{T_r}{N}\frac{1}{\eta_{red}} \\ &= \left(J_m + \frac{J}{N^2}\frac{1}{\eta_{red}}\right)\alpha_0 + \left(\frac{b}{N^2}\frac{1}{\eta_{red}}\right)\omega_0 + \frac{T}{N}\frac{1}{\eta_{red}}\end{aligned} \quad (3.27)$$

Considering the rolling machine theory such as in [3], the machine can be simplified by a rolling force relationship such as the one developed in [8]:

$$F = W\sin\theta + f_r\cos\theta + R_a \quad (3.28)$$

Where W is the load on the rolling machine, θ is the grade of the road, f_r is the rolling coefficient, and R_a is the aerodynamic resistive force.

4. APPLICATION EXAMPLES

AUTOMOTIVE TRANSMISSION DRIVE – As a first example illustrating the use of hybrid models, an automotive transmission drive system will be modeled using Automation Studio™ software. This drive allows the automatic adjustment of the pump and motor displacements to accommodate different load conditions.

In order to get the most out of this type of system, each element in the power transfer chain must function in its optimal yield region.

Classic approach – As an example, an Upstream, transfer-function based approach is developed here. The transfer function is based on the equations introduced in section 3.

In order to simplify the study, we will assume the following:

$$\begin{cases} N = cst \\ V_1 = V_2 = cst \\ p_1 >> p_2 \\ p_c \approx 0 \\ T_0 = cst \\ \mu = cst \end{cases} \quad (4.1)$$

Applying the Laplace transform to the continuity equations yields:

$$D_p\omega_i = D_m\omega_0 + c_t p_1 + \frac{V_0}{\beta_e}sp_1 \quad (4.2)$$

If we consider a linear relationship between the pump displacement and the swash-plate angle, we obtain:

$$D_p\omega_i = k_a\phi \quad (4.3)$$

We write the load dynamics on the motor:

$$\eta_{mm}p_1D_m = (Js + B)\theta^2 + T_L \quad (4.4)$$

The global transfer function becomes:

$$k_a\phi = \omega_0\left(\frac{1}{G_1(s)}\right) + T_LG_2(s) \quad (4.5)$$

Where;

$$\frac{1}{G_1(s)} = D_m\left[\begin{array}{l}\left(\frac{JV_0}{n_mD_m{}^2\beta_e}\right)s^2 \\ +\left(\frac{c_tJ}{\eta_{mm}D_m{}^2} + \frac{V_0B}{\eta_{mm}D_m{}^2\beta_e}\right)s \\ +\left(1 + \frac{c_tB}{\eta_{mm}D_m{}^2}\right)\end{array}\right] \quad (4.6)$$

and

$$G_2(s) = \frac{1}{\eta_{mm}D_m}\left[c_t + \frac{V_0s}{\beta_e}\right] \quad (4.7)$$

We can easily see that such a transfer function can quickly get cumbersome, especially considering the fact that it was obtaining by imposing a lot of assumptions and simplifications which render the model useless in many real-world applications.

Hybrid Approach – The hybrid approach used in the modeling of this transmission system will allow us to focus on the practical aspects of the transmission system.

Starting with the pump, we can view the model as being an assembly of elementary sub-components that already contain their own simulation model. From this point of view, it is possible to adjust individual local parameters using a Downstream approach, without having to readapt the integration of the elementary components; for example, changing the displacement of the rotative group or that of the charging pump, etc, such as show schematically in Fig. 15 for general closed-loop pump integration hybrid model.

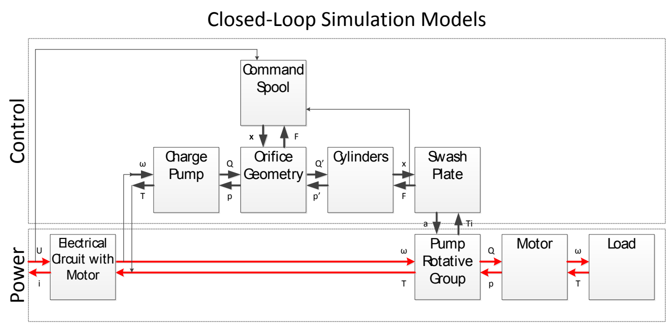


Fig. 15: Integration of Hybrid Models – Closed-Loop

To demonstrate this approach by an application example, we take a real pump such as the Linde Series 02 Pump with CA control. This pump has two main displacement regulation modes, and it is specifically these characteristics that are practical and relevant. The simulated pump model is shown in Fig. 16.

On one hand, the rotation of the thermal engine (1) drives the charging pump (2), which creates pressure at the orifice (3). If the rotation speed is high enough, this pressure will actuate valve (4). By actuating one of the solenoid-operated valves (5), the pressure is transferred to the corresponding side of the servo-cylinder (6), which will change the main pump's displacement (7). This first mode allows adapting the main pump's displacement to the engine's rotation speed.

On the other hand, the changing load creates a working pressure sensed by the opposite side of the servo-cylinder (6), reducing the main pump's displacement. The unit change of the displacement with respect to a unit change in working pressure is conditioned by the power regulating valve (8). Consequently, the power can be maintained at a specific level, which is the second mode of regulation.

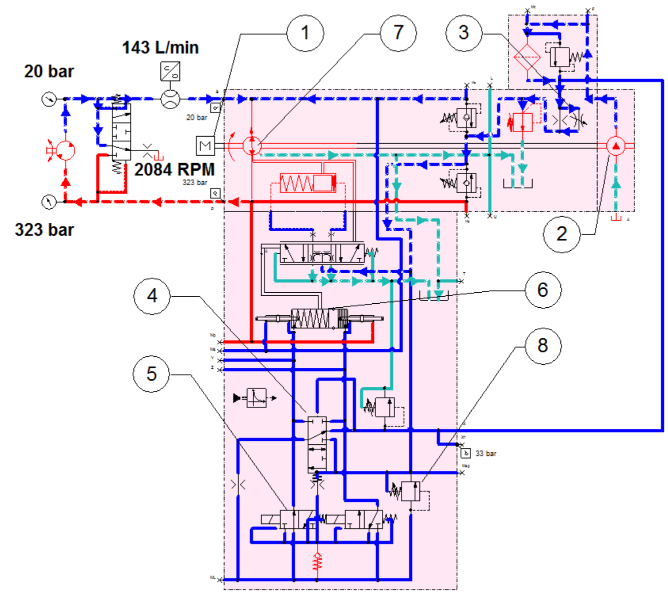


Fig. 16: Linde Pump CA Control Simulation Model

Simulating these characteristics allows the designer to analyze the integration of this pump with the thermal engine. Based on the power consumption and generation characteristics of the engine in use, which is also modeled using the hybrid approach, the simulation will allow the designer to identify what adjustments are necessary to maintain the pump at the optimal point where the engine's power throughput is maximized but where stability is not compromised by being too close to the engine's stalling point.

The study of the hydraulic motor may be conducted in a similar fashion to identify the optimal settings that would optimize the global efficiency of the system.

Performance Analysis – From transmission design criteria, a virtual test bench can be built to test the transmission's performance. Each of the hybrid elements involved in the power transmission chain may be changed and different combinations of complete transmission systems can be tested.

Fig. 17 shows a hydrostatic transmission built using Linde Series 02 axial piston components, including a variable displacement HPV-CA pump and a variable displacement HMV-CA motor. It shows how the output speed and torque change when the actuators are powered. We can then easily analyze the output performance, study the power transmission characteristics, and verify the impact of various parameters, which leads to sound decisions regarding which components to use and how to tune them.

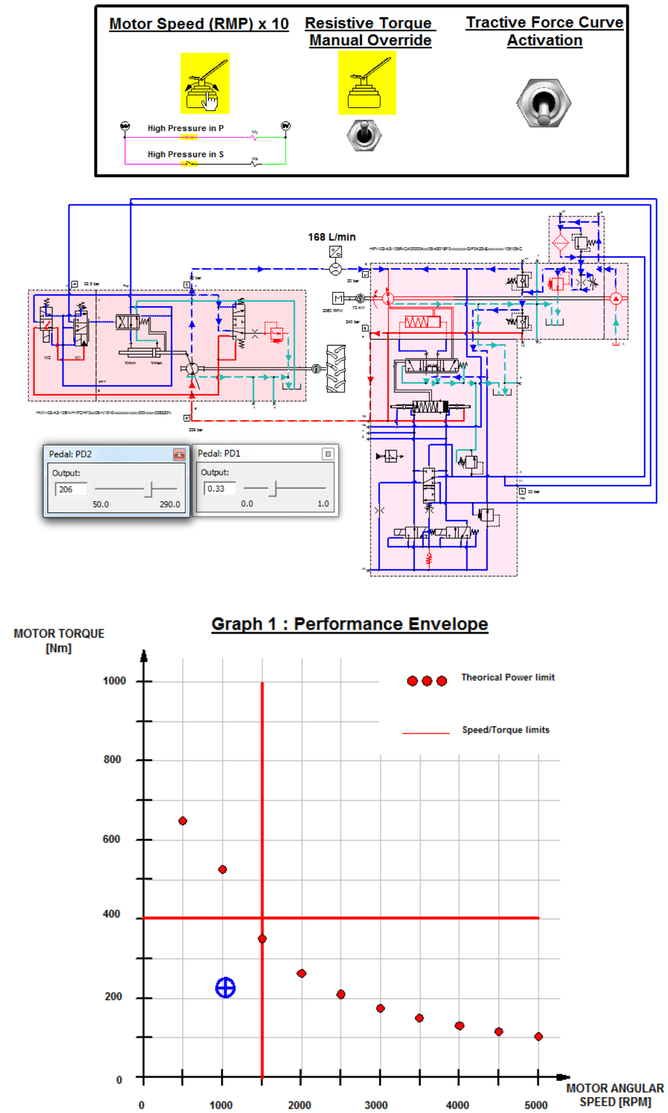


Fig. 17: Performance Analysis of Complete Transmission

Efficiency Analysis – As already stated in section 2, this hybrid approach is especially adapted to focus on energy aspects of transmission systems. Fig. 18 shows the energy level transferred by each element in the transmission chain, which allows the designer to quickly visualize the efficiency level of each element. Moreover, the model of the pump and motor take into account the effect of the fluid's viscosity, which allows for a more detailed study and the analysis of temperature-related phenomena.

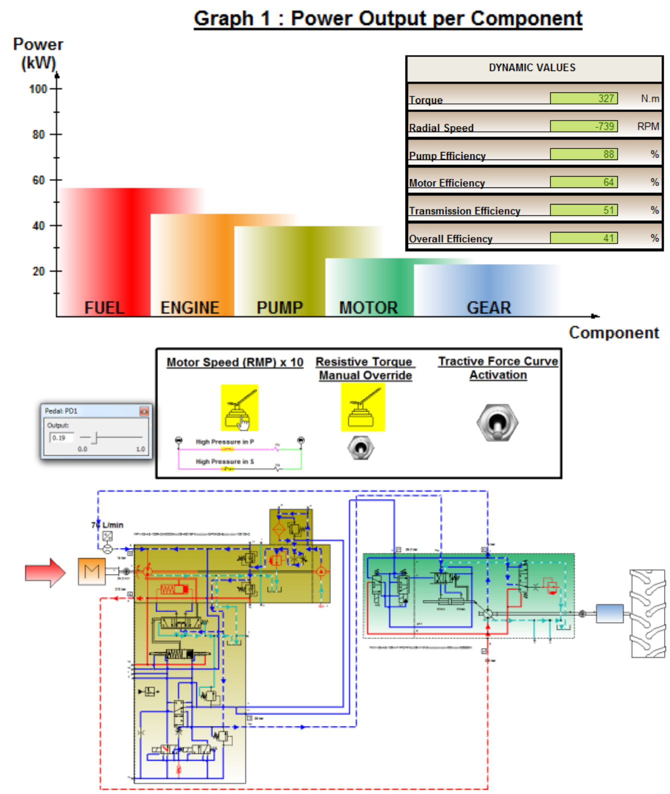


Fig. 18: Efficiency Analysis of Complete Transmission

The hybrid approach used in modeling a hydrostatic transmission system helps to conduct advanced performance and efficiency analyses. Because all the relevant information is encoded in individual components that are relatable to the designer, their integration becomes straightforward, even in multi-level or multi-technology applications.

ELECTROHYDRAULIC OPEN-LOOP LOAD LIFTING CIRCUIT – In [8], a comparison study built using Automation Studio™ software between fixed displacement and load-sensing applications is presented. The study showed that a load-sensing setting has definite advantages, because fixed-displacement systems evacuate considerable amounts of flow at high pressure, which is responsible for significant energy waste. However, further study shows that load-sensing applications are not always more advantageous than fixed-displacement applications. Indeed, the former involves much higher initial investment. Furthermore, when the work cycle is known in advance and when the loads are relatively constant, a traditional proportional circuit may be more economical, because pressure differentials required to regulate a load-sensing system generate power losses that can be avoided when the load profiles are known in advance.

It is therefore interesting to study a system in both fixed-displacement and load-sensing settings, so that the best setting can be identified. The following example illustrates an open-loop system under different actuator speed regulation settings. These different settings will be analyzed and compared.

Hybrid Approach – Here we develop the hybrid model of a system driven by a pump regulated by an electro-hydraulic feedback loop, shown in Fig. 19. Unlike traditional hydraulic or mechanical load-sensing applications, this system regulates the flow by using an electric transducers (1) to sense the pressure differential through a control orifice. The transducer sends the pressure differential signal to an electrical controller (2) that calculates the appropriate response amplitude to be sent to an electrically operated proportional valve (3) that controls the pumps swash-plate (4). The electric transducer, controller and valve solenoid are also modeled using the hybrid approach.

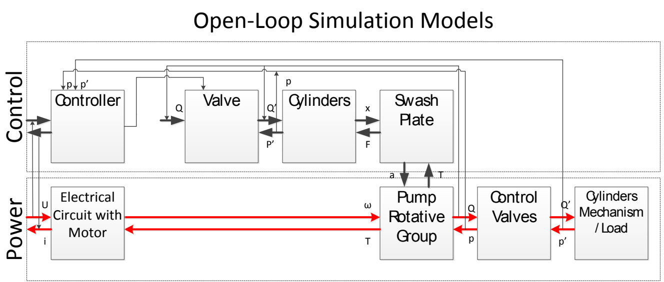


Fig. 19: Integration of Hybrid Models – Open-Loop

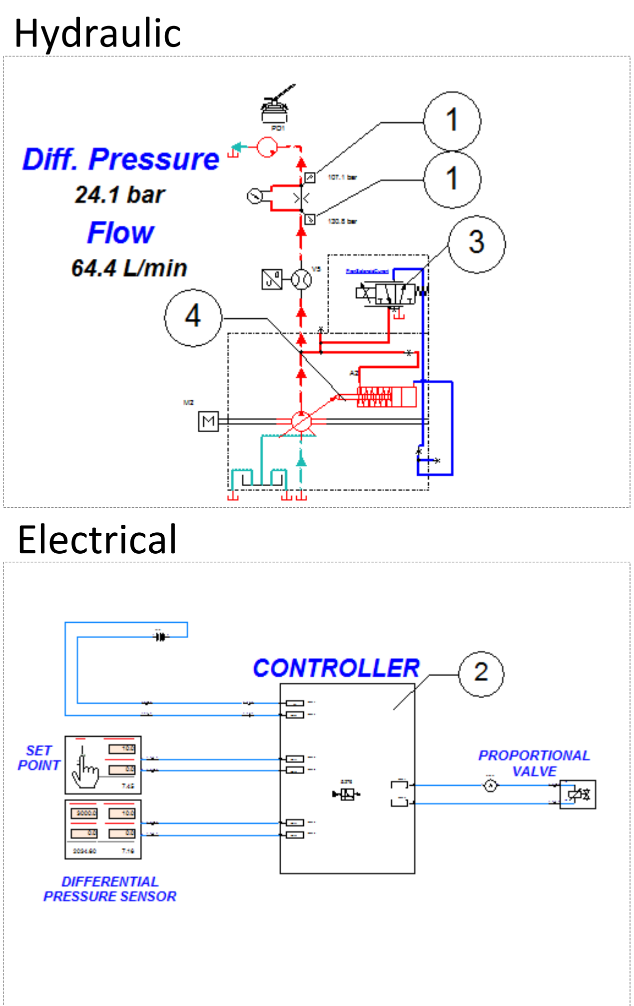


Fig. 20: Electrohydraulic Pump Model

Performance Analysis – Here Electro-hydraulic regulation systems are notoriously non-linear and complex to model, especially when the dynamics of all the components involved have to be considered. Indeed, each element in the loop will contribute to some lagging, affecting the overall stability and response characteristics of the system.

Fig. 21 illustrates the flow regulation in the electro-hydraulic system described above. It shows the time response of both the flow and pressure differential after a ramp modification in the reference setting of the differential setting.

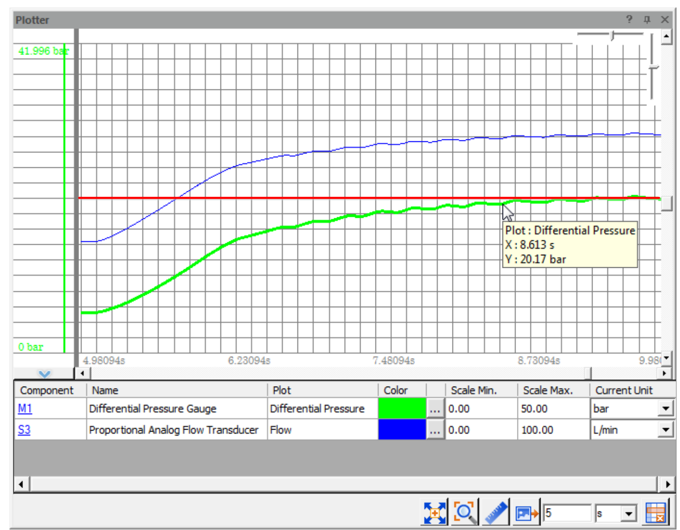


Fig. 21: Response of Electrohydraulic Regulated Pump

Efficiency Analysis – Once the electro-hydraulic pump is modeled, it becomes straightforward to establish a virtual test bench that examines the power characteristics of the electro-hydraulic pump as compared to a standard fixed-displacement pump/

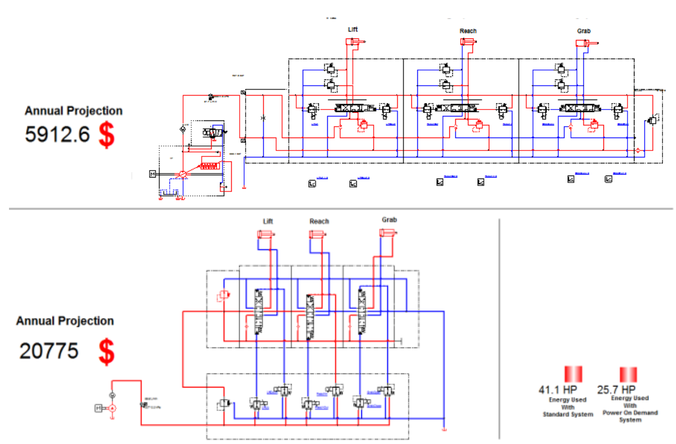


Fig. 22: Energy Consumption Comparison

The circuit in Fig. 22 is built using Eaton load sensing and load independent CML60 valves. It is compared with a traditional proportional circuit with a fixed displacement pump and proportional CM80 valves from the same manufacturer. Their flow characteristics were explained in [8].

5. CONCLUSION

In summary, this study focuses on the multi-technology and multi-level integration that is facilitated by the hybrid modeling approach. By following this paradigm, it becomes possible to model any type of system and to quickly interchange individual modules to analyze novel architectures. Such studies will give valuable insight on system efficiency, stability, control, and implementation and operation costs before resorting to costly prototypes early-on.

An innovative hybrid simulation approach has been presented. This approach allows taking into account any level of fundamental equations within each component used in a global power transmission chain. Also, to provide a more realistic behavior that is not easily modeled by physical equations, a set of lookup tables or characteristic curves can be used. The combination of both these points of view within the same component will allow for highly realistic simulations in a variety of settings that don't need to be predetermined in the modeling phase.

This approach was illustrated using two typical hydraulic circuits. The study was not limited to a purely hydraulic system; it integrated a variety of technologies: electrical, mechanical, and hydraulic. The main focus was put on energy performance criteria.

The hybrid modeling approach proved to be particularly effective in building complex and intricate systems when using pre-configured components from manufacturer e-catalogs.

In order for the various industries to effectively optimize their production cycles, a real need for system virtualization exists. In order to have a widespread, standardized use of virtual systems, a common, modular language of modeling must be used. The hybrid model that we introduced constitutes a significant step in that direction. Furthermore, the benefits of such an approach are amplified when large collections of manufacturer catalogues become more and more available. It is worthy of note that many manufacturers have already started to follow that trend by offering virtual models of their components.

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Richard Gagné is a Mechanical Engineer specialized in system design and simulation with a Master degree in engineering. He has joined the Product team of Automation Studio - Famic Technologies Inc. in 2005 and is now the Quality System Manager. He has cumulated more than 700 hours of training on Automation Studio Software. He has 18 years of experience as a professional engineer and a trainer in academic and industrial environment.

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