Session 2220

A SOFTWARE TOOL FOR UNDERSTANDING NONLINEAR PHENOMENA IN HYDRAULIC AND PNEUMATIC SYSTEMS

Tony Wong[1], Pascal Bigras[1], Daniel Cervera[2]

[1]École de technologie supérieure, Université du Québec / [2]Collège de Valleyfield

1. Introduction

Hydraulic and pneumatic systems are highly nonlinear and difficult to analyze. These systems exhibit nonlinear behavior because of restricted flows, finite cylinder length and non-negligible static and dynamic frictions. Pneumatic system non-linearity is even stronger because of air compressibility. It is always a challenge to explain the effects of these nonlinear phenomena on the overall system behavior. This paper presents a software tool developed to help students understand these complex phenomena without resorting to sophisticated finite element analysis.

In order to achieve this goal, we first define a set of domain concepts that are central to the modeling and understanding of hydraulic and pneumatic phenomena (section 3). We then proceed to identify the most important misconceptions carried by students who don't have a good grasp of the phenomena (section 4). This identification task is based on a constructivist model of the learning process. Particularly the constructivist paradigm and the model of conceptual conflict (section 2). Finally, we design and construct a software application tailored to help correct those misconceptions (section 5). Thus, the focus point here is to design an environment that enables the learner, in conceptual conflict, to reach cognitive equilibrium by reorganizing his conceptual structures. The specific environment discussed in this paper is a software application. Its aim is to facilitate learner – subject interactions through experimentation and to assist the learner in reorganizing his conceptual structures.

2. Constructivist model of the learning process

The inability to explain simple physical phenomenon and a student's own mental representation of the situation have been linked by a number of classical works[1]. These observations give rise to the so-called Constructivist Paradigm of Learning. Within this paradigm, the learning process is a gradual construction process based on the interactions created between the learner and the knowledge to acquire. It is the richness of these interactions that realizes the wealth of the learning process.

According to Piaget, while interacting with the knowledge subject, the learner will encounter situations that lead to cognitive disequilibrium – the learner will question his own representations. He will react and try to reestablish his cognitive equilibrium. This equilibrium reestablishment involves two indissociable mechanisms, which are: assimilation and accommodation[2]. In this context, the assimilation mechanism is the integration of new knowledge in an existing framework. While the accommodation mechanism is the reworking of an assimilation framework to the conditions of a particular situation.

There exists a complementary view of the working principal pertaining to the assimilation and accommodation mechanisms. According to this point of view, the new knowledge integration process is harmonious if the learner possesses the required conceptual structures. Otherwise, the learner must rearrange his own epistemological postulates, and subsequently, the reorganization of his conceptual structures. This is the basic idea underlying the so-called Model of Conceptual Conflict[3]. In this model, a conflicting situation arises when the leaner realizes that his representations can not adapt to new notions and ideas. During this phase, the learner is receptive to some conceptual shifting if it can enable him to reconcile the new situation to his pass experiences. Thus, the necessary conditions that may lead to a conceptual structures reorganization are[3]: *i*) The learner realizes the shortcomings of his own representations in explaining an observed phenomenon; *ii*) There exists a new way to understand the phenomenon; *iii*) The new way of understanding must be seen as plausible; *iv*) The new representation should provide hints to the outcomes of other phenomena already encountered and would incite the learner to test out new hypothesis.

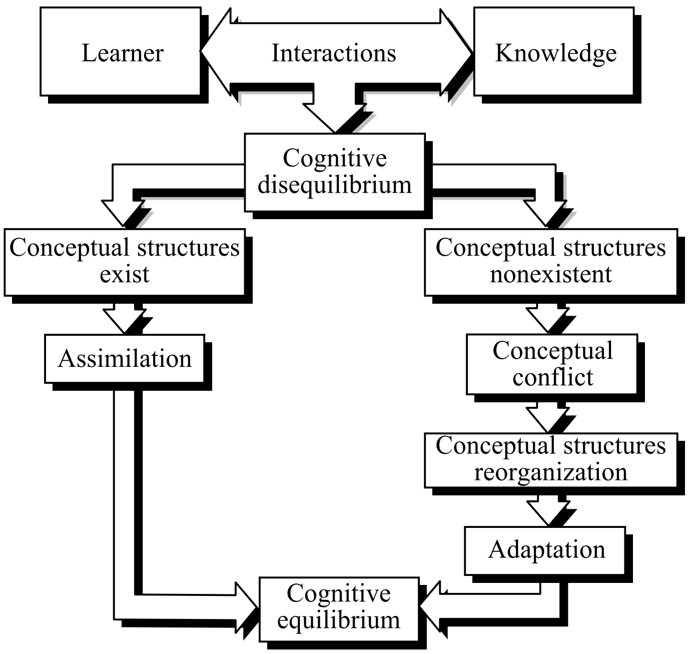

Figure 1. Constructivist model of the learning process.

The figure 1 shows the global constructivist model of the learning process. Note that the assimilation and accommodation mechanisms are shown as the result of conceptual disequilibrium.

3. Domain concept analysis

In this section we will derive domain concepts by the use of functional decomposition. A central abstraction in all technological systems is the notion of energy. In general terms, the modeling of a technological system is to establish predictable relations between a set of actions applied to system components (inputs) and a set of components responses to the applied actions (outputs). Thus, the global function of a system describes the relationships between its inputs and outputs. The global function of hydraulic and pneumatic systems is to transmit the necessary energy to act on machines and different peripheral equipment. The inputs are the flow of energy and actions that modifies this flow. The resulting outputs are the component behaviors in terms of dynamical quantities such as force, torque, acceleration and speed. In fluid systems (meaning hydraulic and pneumatic systems), this global function may be organized into three basic functions: *i*) Energy transmission; *ii*) Energy modulation; *iii*) Thermal stability and fluid conditioning. We can further subdivide these basic functions into related sub-functions. The table 1 summarizes these sub-functions[4].

Table 1. Fluid system sub-functions.

1. Energy transmission	
1.1	Transformation of mechanical energy into fluid energy The mechanical energy is applied to the system as angular speed and torque. The mechanical energy is then converted into fluid energy as flow rate and pressure by a pump or a compressor.
1.2	Transformation of fluid energy into mechanical energy It consists of energy conversion from pump or compressor into mechanical energy in translational form (force and speed) or rotational form (torque and angular speed).
1.3	Fluid energy distribution The fluid circulation within the system can be controlled by opening, closing or forking a set of conducts.
1.4	Fluid energy storage and release In the storage phase, the fluid energy is converted into potential energy by means of fluid accumulation under pressure. In the release phase, the pressurized fluid is discharged producing useful work.
2. Energy modulation	
2.1	Modulation of force and torque This is accomplished indirectly by inflecting changes to the fluid pressure.
2.2	Modulation of speed This is also accomplished indirectly by varying the flow rate that feeds into cylinders or motors.
3. Thermal stability and fluid conditioning	
3.1	Thermal stability This is to maintain system temperature within acceptable limits by cooling down or heating up the system. Thermal instability can be caused by excessive losses within the system. Particularly the loses of volumetrical efficiency.
3.2	Fluid conditioning This is the removal of solid particles from the circulating fluid. Particles can cause mechanical damage to system components.

These sub-functions can be realized by interconnecting together basic hydraulic and pneumatic components such as pumps, motors, pressure valves, flow valves, accumulators, heat exchangers, compressors and distributors. In fact, it is their complex interactions that result in all sub-function realizations. By studying each basic component's behavior model, it is possible to identify useful domain concepts that are important to the fluid system sub-functions. Table 2 is the domain concepts/system functions matrix obtained from this analysis[4].

Table 2. Important and essential concepts related to system sub-functions.

	Fluid system functions						
	Energy transmission			**Energy modulation**		**Thermal stability and fluid conditioning**	
CONCEPTS	Trans-formation	Distribu-tion	Storage/ Release	Force (pressure)	Speed (flow rate)	Thermal stability	Fluid conditioning
Pressure	■	■	■	■	■		■
Vacuum	■						■
Pascal's principal	▒	▒	▒	▒	▒		
Flow rate	■	■	■	■	■		■
Flow rate rules	▒	▒	▒	■	■		
Energy and transformation.	■	■	■	■	■	■	
Bernoulli's conservative law	▒	▒		▒	▒		
Power	■		▒	▒	▒	■	
Efficiency	■			▒	▒	■	
Heat transfer						■	
First-order system						■	
Compressibility/ incompressibility	■		■	▒	■		
Reversibility	■						
Viscosity	▒	▒		▒	■	▒	▒
Flow type	▒	▒		▒	▒	▒	▒
Gas laws			■				

Essential concepts ■ Important concepts ▒

There are four groups of concepts that contribute to the system sub-functions. The first three of these groups concern the central concepts and their associated or derived concepts. While the fourth group concerns other concepts that are not related. The central concepts are the pressure, flow rate, energy and its multiple manifestations.

4. Misconception identification

It has been noticed that students having learning difficulties can not explain or resolve apparently simple problematic situations. Even when the solution to these problems does not involve any calculation but simple qualitative description of the observed phenomenon. The students in difficulty were unable to establish a correct relationship between: *i*) the situation confronting them; *ii*) the phenomenon observed; *iii*) the concepts implied. This inability to formulate a correct tripartite relationship is the result students' misconceptions[5].

In Cervera[6] and in Youssef[7], the idea of misconception was explored in the field of fluid mechanics. Their studies involved groups of technical college students and first-year university engineering students. It was shown that most students exhibit confused reasoning when asked to explain simple observations using domain concepts enumerated in table 2. Below is an extract of some answers taken from Cervera's student survey[6]. Authors' commentary is shown in bold characters enclosed within parenthesis.

" Pressure is itself a material entity (**false**). It is produced by a pump (**false**). We can circulate, manipulate the pressure or use it to move a cylinder (**false**). Pressure is a function of the fluid's flow rate (**partially true**). The smaller the pipe the faster is the flow and the pressure is higher (**partially true**). Thus, a cylinder's strength depends on the size of the pipe (**false**). "

The students perceive the "pressure" not as an explanatory concept but as a real physical object. For them, pressure as a physical object, can be moved around within the system. And it is this physical object that acts on the cylinder's piston and thus making it moves. Also, they consider a proportional relationship between the pressure and flow rate. By a similar deduction process, they conclude that the force produced by a cylinder is a function of the size of the connecting pipe.

We believe that the major factor contributing to these misconceptions is the nonlinear relationships governing the pressure and the flow rate in fluid systems. Students tend to relate quantities in linear or proportional terms. Their faulty representation is often the result of the general application of an idea, which states that nonlinear behaviors can be approximated by linear ones when the variations are small. As we will show, this is not always true in fluid systems even in very simple cases. Consider a simple hydraulic setting with a single restriction and the fluid is assumed to be non compressible. This setting is illustrated in figure 2.

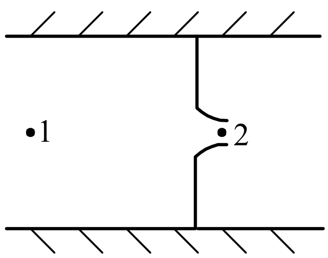

Figure 2. One dimensional fluid flow with single restriction.

We shall neglect the effects of gravity and assume the velocity of the fluid at point 1 as negligible compared to that of point 2. Using Bernoulli's equation, we have[8]

$$P_1 = P_2 + \tfrac{1}{2}\rho V_2^2 \tag{1}$$

where P_i is the pressure at point i, V_i is the velocity of the fluid and ρ its density. If we consider that the opening surface at point 2 is A then the relation between the flow rate Q and the pressure difference at points 1 and 2 can be written as

$$Q = A\sqrt{\tfrac{2}{\rho}}\sqrt{P_1 - P_2}\,, \tag{2}$$

where $V = Q / A$. Evidently, this flow rate is not a linear function of the pressure. Moreover, simple linear approximation does not hold when the pressure difference is near zero. Consequently, most students will have difficulty conceiving the correct representation of this phenomenon.

We now turn the one dimensional fluid flow of figure 2 into a pneumatic setting. The pneumatic setting is highly nonlinear because gas is compressible. We shall again neglect the effects of gravity. The differential form of Bernoulli's equation gives[8]

$$\frac{dP}{\rho} + \frac{1}{2}d(V^2) = 0\,, \tag{3}$$

where ρ is a function of the pressure P. If we assume an isentropic process for the fluid flow and apply the ideal gas hypothesis then we have

$$\rho = P^{\frac{1}{k}} C^{-\frac{1}{k}}\,, \tag{4}$$

$$\rho = \frac{P}{RT}\,, \tag{5}$$

where R is the gas constant, k is the specific heat coefficients' ratio, T the temperature and C a constant. By replacing equation (4) into equation (3) and integrating between point 1 and point 2, we get

$$C^{\frac{1}{k}} \frac{k}{k-1}\left(P_2^{(k-1)/k} - P_1^{(k-1)/k}\right) + \frac{1}{2}\left(V_2^2 - V_1^2\right) = 0\,. \tag{6}$$

Again, we assume the velocity of the fluid at point 1 as negligible compared to that of point 2. Knowing that $V = Q / A$, the flow rate at point 2 can easily derived by combining equations (4), (5) and (6). The flow rate at point 2 is described by

$$Q_2 = A\sqrt{RT_1}\sqrt{\frac{2k}{k-1}}\sqrt{1-\left(\frac{P_2}{P_1}\right)^{(k-1)/k}} \tag{7}$$

which is a highly nonlinear function of P_1 and P_2. To further complicate the situation, the flow rate is different at point 1 and point 2 since gas is compressible. Most students will at first be confused by this phenomenon. To bypass this difficulty, we can instead use the mass flow $\dot{m}$. Because of mass conservation, mass flow is invariant along a pipe. The mass flow is related to fluid flow by

$$\dot{m} = \rho_2 Q_2\,. \tag{8}$$

By combining equations (4), (5), (7) and (8),we can derive the following mass flow expression

$$\dot{m} = \frac{AP_1}{\sqrt{RT_1}}\sqrt{\frac{2k}{k-1}}\sqrt{\left(\frac{P_2}{P_1}\right)^{2/k} - \left(\frac{P_2}{P_1}\right)^{(k+1)/k}} . \tag{9}$$

In practical situations, we need to take into account an additional effect in the mass flow expression. It is the so-called diffusion phenomenon[9] where the fluid velocity at point 2 cannot exceed the speed of sound. When the fluid velocity at point 2 equals to that of sound, lowering the pressure at the restriction's output will not cause the mass flow to increase. With this added phenomenon, we have to rewrite equation (9) as

$$\dot{m} = \begin{cases} \dfrac{AP_1}{\sqrt{RT_1}}\sqrt{\dfrac{2k}{k-1}}\sqrt{\left(\dfrac{P_2}{P_1}\right)^{2/k} - \left(\dfrac{P_2}{P_1}\right)^{(k+1)/k}} & \text{if } \dfrac{P_2}{P_1} < r_c, \\ \sqrt{k\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}} & \text{if } \dfrac{P_2}{P_1} \geq r_c, \end{cases} \tag{10}$$

where

$$r_c = \left(\frac{2}{k+1}\right)^{k/(k-1)} . \tag{11}$$

Because of these cascading considerations, the final mass flow expression has the form of a piecewise function. Even in such a simple setting, fluid systems exhibit non-linearity. In a more practical setting where basic fluid components are involved, the relationships must include other nonlinear phenomena. For example, fluid accumulation in a cylinder is a function of volume variations caused by rod displacement. This nonlinear relationship results in the coupling of the fluid part and the mechanical part of the system. Furthermore, the mechanical part also possesses nonlinear characteristics such as finite piston length, static and dynamic frictions. All these nonlinear characteristics and phenomena contribute to the overall complexity of most simple fluid systems.

5. Software tool design

As shown in section 4, fluid systems are highly nonlinear. In fluid systems no single law exists which describes the resistance of passages to flow. And simple explanatory models are difficult to obtain due to the analytical complexity involved. Numerical simulations provide a mean to bypass these analytical difficulties. Simulation packages such as NASA's FAST[10] for transient fluid flow studies and Boeing's EASY5[11] for general computational fluid dynamic analysis are suitable for large-scale design problems and fine-grained analysis. Both packages require high-end computers and in-depth knowledge of the engineering discipline. Small-to-medium scale system analysis packages such as MathWorks' Hydraulic blockset[12] and PNEUMA[13] do not provide visual feedback which could enhance the representation of the underlying physical phenomena. Also, most simulation packages do not permit explicit hydraulic and pneumatic coupling. In practical system assemblies both hydraulic and pneumatic components may operate concurrently. It should be interesting to study their interplay without performing complicated conversions and transformations. Thus, our goal is to fulfill the need for a software tool capable of handling small-to-medium scale fluid systems with the following characteristics:

1. Graphical system construction.
2. Visual feedback using graphical animation synchronized with solver outputs.
3. In-simulation interactivity between student and circuit components.
4. Arbitrary connection of measurement points (instrumentation) for data collection.
5. Continuous and step-by-step simulation modes.
6. Fast and accurate quasi real-time iterative numerical solver for nonlinear algebraic equations.
7. Coupling between hydraulic and pneumatic components via mechanical components.
8. Highlight behavioral differences between hydraulic and pneumatic systems.

These characteristics are defined so to facilitate student – subject interactions through experimentation and to assist the student in reorganizing his conceptual structures. In order to obtain the above mentioned desirable characteristics, we need to employ a systematic and efficient approach for the design and implementation of the software tool. By modeling all hydraulic, pneumatic and mechanical components as multi-port devices, one can apply the bond graph theoretic approach for circuit topological recognition[14]. The bond graph approach is a general technique that results in system equation formulation. It is well suited to the problem of hydraulic, pneumatic and general mechanical systems because of its so-called causality analysis capability[15].

In our design approach, all components are modeled as multi-port devices (see figure 3). There are two variables associated with each device port. They represent the effort-quantity (pressure, force, etc.) and the flow-quantity (flow, speed, etc.) of the device. However device port's directional information is not known a priori. That is, input-output relationship of the device ports is dependent on the circuit's topology. By using bond graph's causality analysis method, one can determine input-output relationship of every connected port on-line[15].

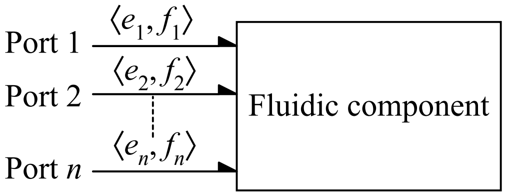

Figure 3. Multi-port device modeling of hydraulic and pneumatic components.

In a typical system circuit, each component is connected to other components by its ports as shown in figure 3. The couple $\langle e_i, f_i \rangle$ represents the effort and flow variables of port i. There will be a total of N ports in the system circuit. The sets $E = \{e_i \mid 1 \le i \le N\}$ and $F = \{f_i \mid 1 \le i \le N\}$ are then partitioned into input and output subsets. As mentioned earlier, each variable's directional information is a function of the component's causality. Thus, there exists for each component port two possible causalities. This amounts to 2^n possible configurations for an n-port component. By applying the causality analysis this can be solved in polynomial time. For each causality, the numerical model of the i^{th} component is a nonlinear ODE system of form

$$\begin{aligned} \dot{\mathbf{x}}_i &= \mathbf{h}_i(\mathbf{x}_i) + \mathbf{b}_i(\mathbf{x}_i, \mathbf{u}_i) \\ \mathbf{y}_i &= \mathbf{g}_i(\mathbf{x}_i) + \mathbf{d}_i(\mathbf{x}_i, \mathbf{u}_i) \end{aligned}, \tag{12}$$

where $\mathbf{x}_i$ is the state vector, $\mathbf{y}_i$ is the outputs vector and $\mathbf{u}_i$ is the inputs of the i^{th} component. The system model comprising all circuit components is

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{H}(\mathbf{x}) + \mathbf{B}(\mathbf{x},\mathbf{u}) \\ \mathbf{y} &= \mathbf{G}(\mathbf{x}) + \mathbf{D}(\mathbf{x},\mathbf{u}),\end{aligned} \tag{13}$$

where $\mathbf{x}$ is the state vector, $\mathbf{y}$ is the outputs vector and $\mathbf{u}$ is the inputs vector of all circuit components. The input-output coupling between circuit components can be modeled as

$$\mathbf{u} = \mathbf{C}\mathbf{y}\,. \tag{14}$$

Finally, the global model of all interconnected component results from the substitution of equation (14) in equation (13) is

$$\dot{\mathbf{x}} = \mathbf{H}(\mathbf{x}) + \mathbf{B}(\mathbf{x},\mathbf{C}\mathbf{y}), \tag{15a}$$

$$\mathbf{y} = \mathbf{G}(\mathbf{x}) + \mathbf{D}(\mathbf{x},\mathbf{C}\mathbf{y}). \tag{15b}$$

We can consider the system equations as an assembly of two coupled subsystems: one depicting the slow varying part and the other depicting the fast varying part of the system. In physical terms, the slow varying part represents the mechanical interactions and the elasticity of the pneumatic fluid. Using similar reasoning, the fast varying part represents the elasticity of the hydraulic fluid.

By application of the singular perturbation theory to our global model, it is possible to transform the set of nonlinear differential equations of the fast varying part into a set of nonlinear algebraic equations[16]. This result greatly facilitates the construction of the numerical solver. An optimized and stabilized adaptive integrator, an integral part of the numerical solver, is used to ensure the accuracy of the solution at each time-step. Note that the global model includes a static part (15b) and a dynamic part (15a). At each simulation pass, we solve the static part first. The integrator using adaptive time-steps then solves the dynamic part of the system. However, because the latter is iterative in nature, it is not possible to guarantee hard real-time performance.

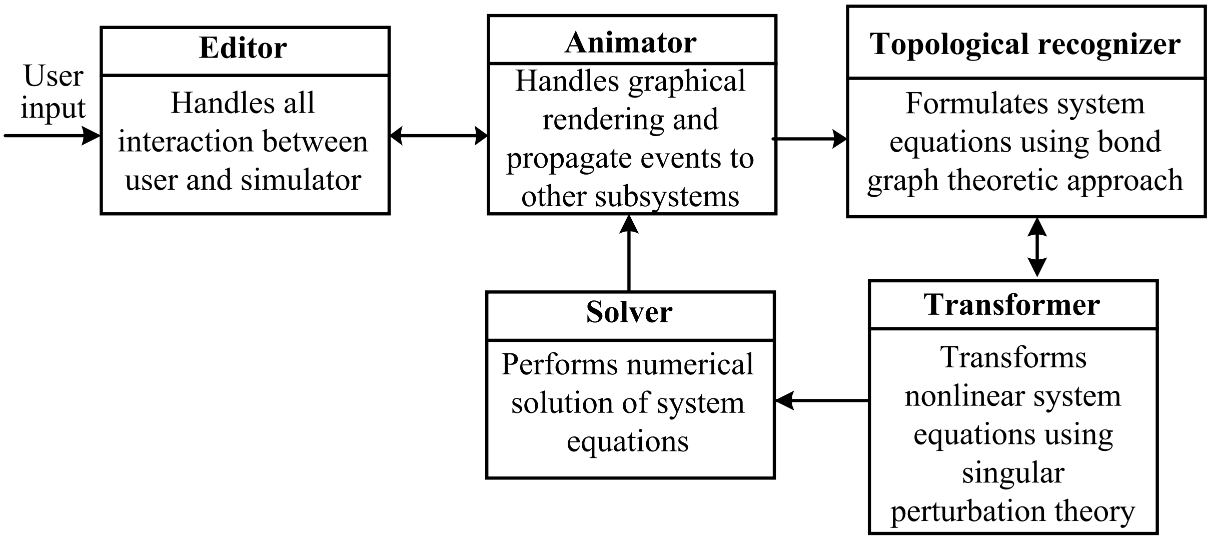

Figure 3. Software tool subsystems.

As shown in figure 3, there is a logical interface between the solver output and the graphical animation subsystem. The latter subsystem is responsible for updating color changes and the redraw of moving parts on behalf of the circuit components. The graphical animation subsystem also collaborates closely with circuit components to allow student to perform in-simulation manipulations. An in-simulation manipulation means student can change or modify a component's state while a simulation run is in progress. Thus, student can stop or start motors, select different distributor pistons, modify cylinder's longitudinal position, etc. In order to allow in-simulation manipulations, the numerical solver must establish a so-called mechanical chain to determine the effect of changes on other circuit components. This involves the recalculation of system variables and a nontrivial graph traversal to propagate these new values to all connected components. It is worth noting that instrumentation (i.e. adding measurement points to the system) does not increase system complexity. Since instrumentation merely associates a set of system variables to the set of output variables, there is no extra overhead in processing instrumentation measurement points. Finally, instrumentation is preprocessed in the causality analysis phase so that no negative impact can affect the overall simulation time.

The result of the software tool design is a simulation package called Hydro+Pneu. It has been in continuous development since 1996. It enables the student to design fluid system circuits and to obtain both quantitative and qualitative results rapidly and accurately. The Hydro+Pneu simulator is the product of education sciences[17], software engineering[18] employing object-oriented approach[19] and advanced system modeling techniques[16].

Hydro+Pneu uses a color-coded scheme to represent state changes in transient regime and transient-to-steady state transitions. Usually, mechanical displacements (linear translations and rotational movement) can be expressed easily by graphical animations. However, dynamic entities such as pressure differential, flow resistance and temperature variations are much more difficult to express. A color-coded scheme is suitable for representing these dynamic variables. In this scheme a set of colors is mapped to a range of variable values. While a simulation is in progress, the student can notice components internal changes by observing its color variations. For a more quantitative evaluation, the student can also connect measurement components to the circuit. These measurement components display numerical data at each time-step. In figure 4 the one dimensional fluid flow with single restriction discussed in section 4 is being simulated by the software tool. The resulting XY graphs clearly show the nonlinear pressure – flow rate relationship for both circuits. By comparing these two graphical outputs, one can easily appreciate the strong non-linearity produced by the pneumatic circuit.

A hybrid hydraulic and pneumatic system is depicted in figure 5. The single contact point is the mechanical interface between the pneumatic and hydraulic cylinders. This hybrid circuit shows an interesting application where a pneumatic cylinder, driven by its compressor group, is the prime moving force. The hydraulic cylinder, which is coupled to the pneumatic one, acts as a retaining force on behalf of the load. Note that this hybrid configuration permits different retaining flows for forward and backward cylinder motions because of the flow controls installed to the hydraulic cylinder. The student can control forward or backward motion by activating the distributor pistons while the simulation is in progress.

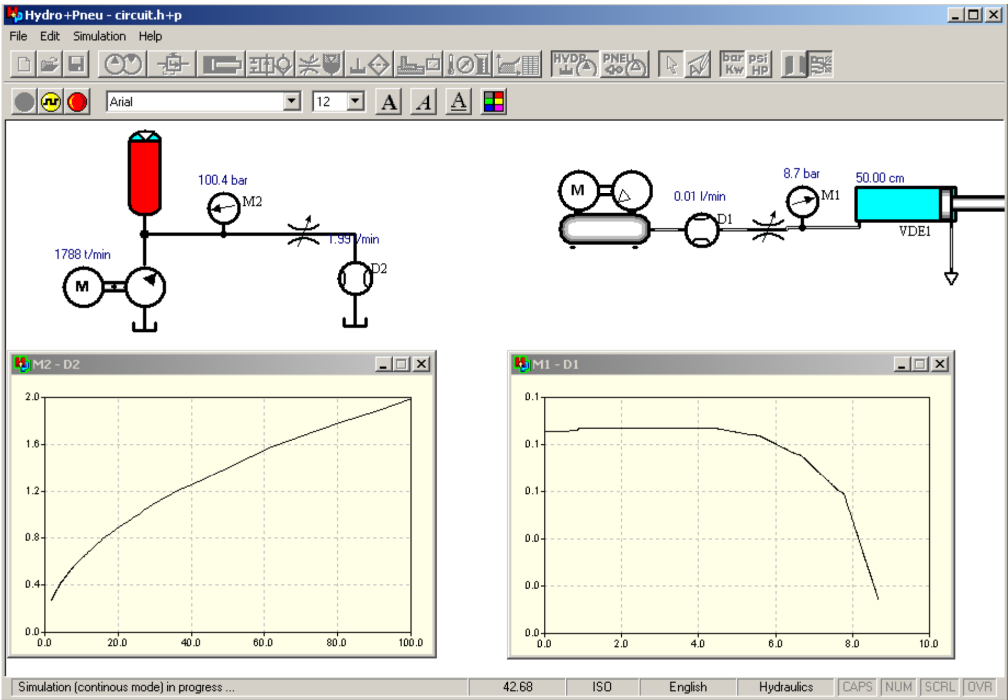

Figure 4. Fluid flow with single restriction: hydraulic case (left) and pneumatic case (right).

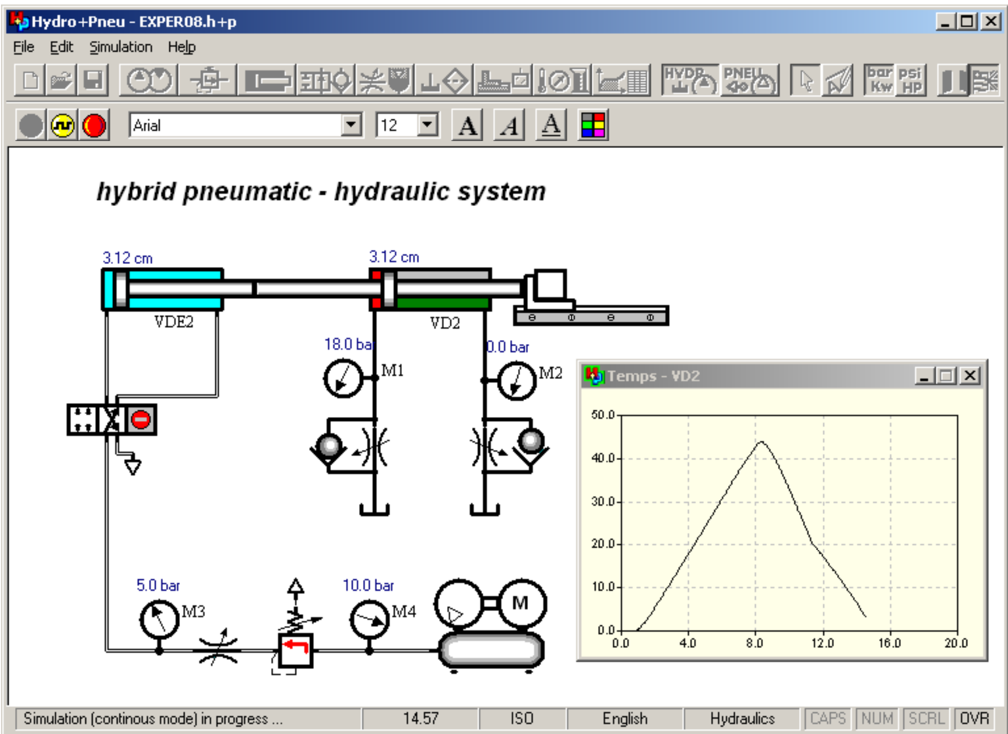

Figure 5. Hybrid hydraulic – pneumatic system.

Every hydraulic, pneumatic and mechanical component possesses a numerical model that is fully adjustable. Figure 6 shows a typical component dialog boxe for parameter input.

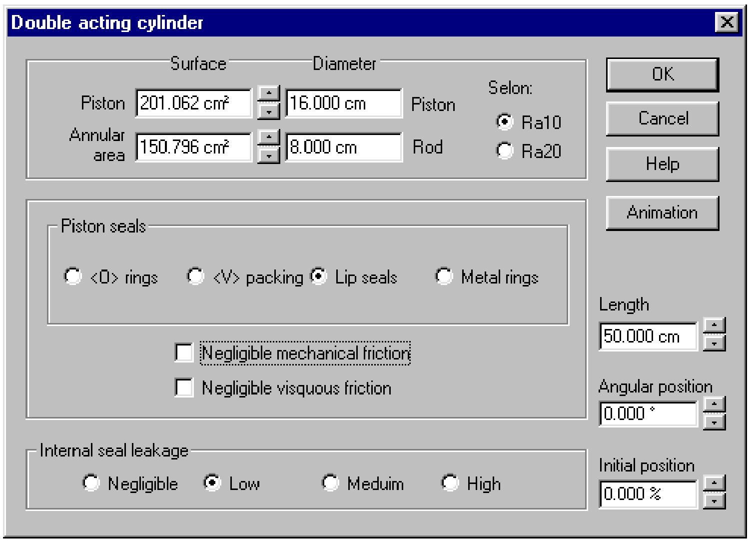

Figure 6. Numerical model parameters for a double acting cylinder.

In most cases, non-ideal component characteristics are possible. For example, figure 6 contains an input dialog box for a double acting cylinder. The student can select from several joint leak degrees (negligible, low, medium and high). The student can also consider or not mechanical and viscous frictions to obtain non-ideal characteristics caused by aging and wear of the component.

7. Conclusion

This paper presented the motivation and the design of a quasi real-time simulator. The intent is to help students understand nonlinear behaviors in fluid systems. This simulator is suitable for small-to-medium scale fluid system analysis and uses a bond graph theoretic approach for system equation formulation. An optimized and stabilized adaptive integrator, an integral part of the numerical solver, is used to ensure the accuracy of the solution at each time-step. The logical interface between the integrator output and the graphical animation subsystem is also discussed. The graphical animation subsystem is responsible for updating color changes and the redrawing of moving parts on behalf of circuit components. The end result is the ability to create the illusion of continuous movement. Finally an important characteristic of this simulator is its ability to permit in-simulation manipulation which allows student to interact with circuit components while a simulation run is in progress. This characteristic may facilitate students to reorganize his conceptual structures by interacting directly with the fluid system under consideration.

Bibliography

1 Catherine, F. (1996), Constructivism: *Theory, perspectives, and practice*. New York: Teachers College Press.

2 Piaget, J. (1964), *Six études de psychologie*. Gonthier, Genève.

3 Posner, G. J., Strike, K. A., Hewson, P. W., Gertzog, W. A. (1982), Accommodation of a scientific conception: towards a theory of conceptual change. *Science Education*, 66 (2), pp. 211-217.
4 Cervera, D., Métioui, A. (1993), *Énergie des fluides: analyse conceptuelle et représentation des élèves*. Technical report (PAREA), Collège de Valleyfield, Québec.
5 Cervera, D. (1998), *Élaboration d'un environnement d'expérimentation en simulation, incluant un cadre théorique pour l'apprentissage de l'énergie des fluides*. PhD dissertation, faculté des sciences de l'éducation, Université de Montréal.
6 Cervera, D., Métioui, A., Youssef, A. Y., Bigras, P. (1991), Les représentations des élèves en hydraulique et l'apprentissage d'un sujet technique. *Congrès de l'ACFAS*, actes du colloque.
7 Youssef, A. Y., Métioui, A., Bigras, P., Cervera, D. (1991), *Les représentations des étudiants du collégial professionnel à l'égard des principes de fonctionnement des circuits hydrauliques*. Technical report, École de technologie supérieure.
8 Munson, R. R., Young, D. F., Okiishi, T. H. (1998), *Fundamentals of Fluid Mechanics*. John Wiley & Sons, New York.
9 Andersen, B. W. (1967), *The Analysis and Design of Pneumatic Systems*. John Wiley & Sons, New York.
10 http://www.nas.nasa.gov/Software/FAST/
11 http://www.boeing.com/easy5/
12 http://www.mathworks.com/products/connections/product_main.shtml?prod_id=212/
13 http://www.mathworks.com/products/connections/product_main.shtml?prod_id=169/
14 Karnopp, D. C., Margolis, D. L., Rosenberg, R.C. (1990) *System Dynamics: A unified Approach*, John Wiley & Sons, New York.
15 Dijk, J. D. (1994), *On the role of bond graph causality in modelling mechatronic systems*. PhD dissertation, University of Twente, CIP-Gegevens.
16 Khalil, H. K. (1992), *Nonlinear Systems*, Macmillan, New York.
17 Giordan, A., de Vecchi, G. (1987), *Les origines du savoir; des conceptions des apprenants aux concepts scientifiques*. Delachaux & Niestlé S. A., Paris.
18 Sommerville, I. (2001), *Software Engineering*, 6th ed. Addison-Wesley.
19 Rumbaugh, J., Blaha, M., Lorensen, W., Eddy, F., Premerlani, W. (2000), *Object-Oriented Modeling and Design*. Prentice-Hall.

Biographies

Tony Wong holds a B.Eng. and M.Eng. degrees from École de Technologie Supérieure in electrical engineering. He received his Ph.D. degree in computer engineering from École Polytechnique de Montréal. Dr. Wong is a professional engineer and adjunct professor at the department of automated production engineering, École de technologie supérieure. His current research interests are multi-objective optimization using evolutionary algorithms and its parallel implementations.

Pascal Bigras received the B.Eng. degree in electrical engineering and the M.Eng. degree from École de Technologie Supérieure of Montréal in 1991 and 1993, respectively, and the Ph.D. degree in automatic control from École Polytechnique de Montréal in 1997. Dr. Bigras is adjunct professor at the École de Technologie Supérieure since 1999. His current research interests are nonlinear and robust control; theory and applications.

Daniel Cervera holds a Ph.D. degree in education sciences from Université de Montréal. Dr. Cervera is a teacher at Collège de Valleyfield for the past 30 years. His current research interests are in the field of abstract representations of technical and scientific knowledge.