Using Home-made Virtual Labs in Higher Education: An Experience in Teaching Power Hydraulics*

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Laboratories have traditionally played a significant role in higher education as a place where students can apply theory to real-life situations. However, most university laboratories have modest facilities that allow the implementation of only a few basic arrangements. In this regard, simulation software can be used to complement basic hands-on practice and also to reinforce previous concepts. This paper presents a home-made educational application used to simulate hydraulic power networks that has been developed by the authors. The application was designed for a virtual subject that employs a blending methodology for laboratory experience. First, the students implement several simple circuits in the laboratory in order to learn the basis of power hydraulics. Next, they can download the application from the web and use it to design, analyse and understand the operation of more complex networks. The effectiveness of the use of the application in the learning process was assessed at the end of the course by means of an opinion survey. The results obtained are presented at the end of the paper.

Keywords: virtual lab; power hydraulics; on-line teaching; distance learning

1. INTRODUCTION

LABORATORIES have traditionally played a significant role in engineering education as a place where theoretical basis can be applied to real hands-on practice. However, the educational laboratories available in universities are often quite modest, thus allowing the implementation of only a few basic arrangements. Also, the teaching methodologies used in laboratories, in most cases, require extensive guidance. In contrast, the guidelines given in the Tuning project [1] and in some accreditation programmes [2] promote the autonomous work of the students. Hence, it would be advisable to complement guided laboratory practice with additional resources that can improve autonomous learning while developing students' professional competences.

In this regard, the widespread use of personal computers and the Internet make it possible to implement on-line educational methods, which have proved to be useful tools to develop and reinforce engineering competences [3, 4]. On-line methods can use remote labs to allow distance manipulation of real instrumentation, thus providing a quasi-real hands-on laboratory experience [5–7]. Also, a virtual laboratory experience can be provided by means of simulation software using commercial codes [8–10]. Commercial programs are powerful and they offer a large variety of modelling capabilities and animation facilities; in contrast, some of the limitations of commercial software are its limited flexibility, lack of compatibility, difficulty to learn, and cost [9]. Virtual labs can be additionally implemented by means of specific home-made software developed for a particular subject [11–15]. While remote labs usually need expensive laboratory equipment located in a specific place, virtual labs are relatively inexpensive, provided that they offer simple simulations that do not require too much computational power.

Although simulation software cannot completely replace physical hands-on experiments, it plays a significant role in engineering education. Simulation programs are used to design and (virtually) manipulate a large variety of physical and technical processes. In addition, they are a useful tool to analyse systems that are too large, expensive, or dangerous to be implemented in a laboratory by students. Also, educational simulations can provide a meaningful laboratory experience [16] and have proven to be equivalent to physical labs for explaining and reinforcing concepts [17].

A home-made educational application used to simulate hydraulic power networks is presented in this paper. The application was developed for an on-line subject that employs a blending methodol-

ogy for laboratory experience. On the one hand, real hands-on laboratory practice is used to teach the basis of power hydraulics through the implementation and analysis of several sample networks. On the other, the application acts as a virtual lab that is used by the students to design, analyse and understand the operation of more complex networks than those implemented in laboratory. The effectiveness of the use of the application in the learning process was assessed at the end of the course by means of an electronic survey [18] that was provided to the students. The results obtained are presented at the end of the paper.

2. STRUCTURE OF THE APPLICATION

The application was designed as a general purpose program that could be used to simulate several kinds of networks (as, for example, electric or pneumatic). Its framework can be divided into six main routines depending on the task performed: (1) the network implementation; (2) the handling of the network figures; (3) the storage of the drawings that represent figures; (4) the link of the figures; (5) the network simulation; and (6) the communication with the user through the interface. The word 'figure' designates any available element that can be introduced in the network (for example: pumps, motors, hydraulic actuators, directional control valves, etc.). Only routines (3) and (5) depend on the hydraulic nature of the network. The software was developed through object-oriented programming using the Borland Delphi language. Figure 1 shows the relationship between the implemented components.

The *network* is built through the TCircuit component (see Fig. 1). This component performs three main tasks:

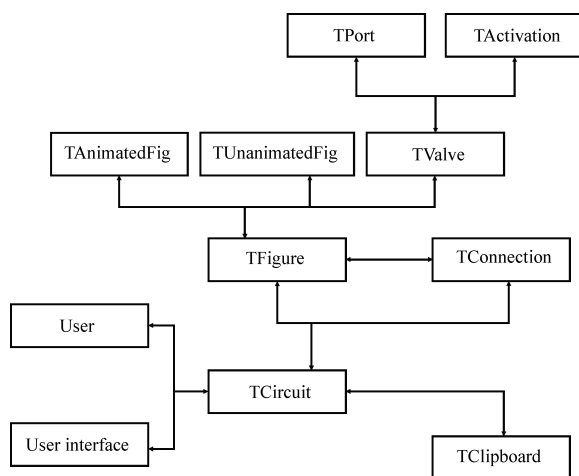1. Communication with the User and the User interface.

2. Storage and implementation of the hydraulic network using the figures selected and the connections created (this is done through the TFigure and TConnection components, as shown in Fig. 1). The TCircuit component holds an internal list of network figures and connections; also, it manages the events caused by the use of the mouse.
3. Control of the simulation process by using the appropriate simulation method for each network figure.

Additionally, TCircuit can use the Windows Clipboard to copy/paste the network figures through the TClipboard component. This is useful for creating a new figure while keeping the properties of the original one. Also, the copied figure can be pasted as a bitmap image in other Windows-based applications.

The word *figure* designates the hydraulic elements that can be introduced in the network, as previously indicated. All the figures available in the application inherit their properties from the TFigure component (see Fig. 1). The components TAnimatedFig and TUnanimatedFig descend from TFigure and are used to implement either animated or static figures respectively. Directional control valves are implemented through the TValve component, which also descends from TFigure. The number of ports available in the control valves and the type of activation is defined using the components TPort and TActivation (see Fig. 1) that descend form TValve. Additionally, user-defined control valves can be designed through the User interface, as explained in the following sections. If a new figure is introduced in the network then the software searches for its associate bitmap drawing in the appropriate program component; once found, the bitmap is pasted in the workspace of the application.

The *drawings* are the schematics on-screen of the figures used in the network, as shown in Fig. 2 for several hydraulic components. There is no single drawing for animated figures but a number of drawings are needed for the complete animation. This is the case, for example, of a set of drawings that simulate the motion of an actuator shaft. Three drawings of different size (that can be selected from the User interface) were implemented for each network figure. The drawings of the same size are stored together as bitmaps into a Dynamic Linking Library (DLL).

The *links* are used to connect the on-screen figures by means of lines that represent pipes. Links are, strictly speaking, not considered to be 'figures', and so they were implemented in an additional component named TConnection (see Fig. 1). This component generates a pointer for each new link created. The pointer is used to store the identifiers of the two linked figures and of the link itself. The TConnection component was also provided with an iterative algorithm used to calculate the best path between two figures. The algo-

Fig. 1. Relationship between the program components.

Actuators   **Flow valves**

Pumps & Motors

Pressure valves

Instrumentation
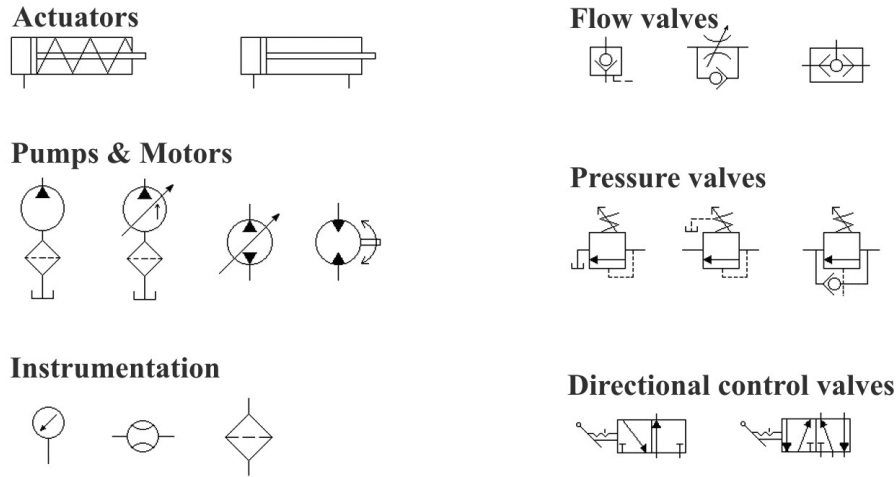
Directional control valves

Fig. 2. Drawings of several hydraulic elements available in the application.
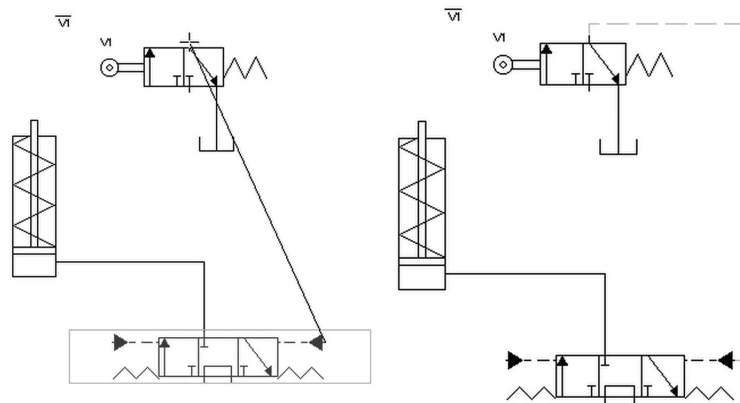

Fig. 3. Sample calculation of the optimum path for the linkage of two valves.

rithm draws the link between the figures rounding previous obstacles, as observed in Fig. 3. This figure shows the implementation of a piloting line between a 3/3 directional control valve and a 3/2 roller valve.

The *simulation* of the network is based on the real operation of hydraulic elements [19, 20]. It is divided into three phases activated from the TCircuit component. Phase 1 starts with the pumps providing the magnitude of theoretical flow rate, which is transmitted through the network. If a flow signal comes across a figure, then the magnitude of the exit flow rate is calculated if necessary (for example, the magnitude of Q_1 in Fig. 4 is obtained from the area ratio of the actuator). This is done until all the signals reach a tank or a hydraulic actuator with no exit route for the fluid. Subsequently, the flow signals are transmitted backwards from these closing figures following the previous paths. This second loop is used to calculate the hydraulic losses and the operating pressure of the actuators from the user-defined loss constants, geometric parameters and loads. The operating pressure in the actuators can be inferred from a steady-state
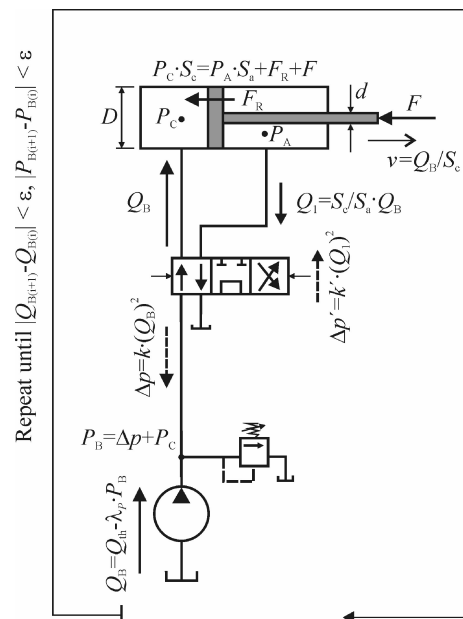

Fig. 4. Iterative procedure and calculation of parameters in a simple circuit.
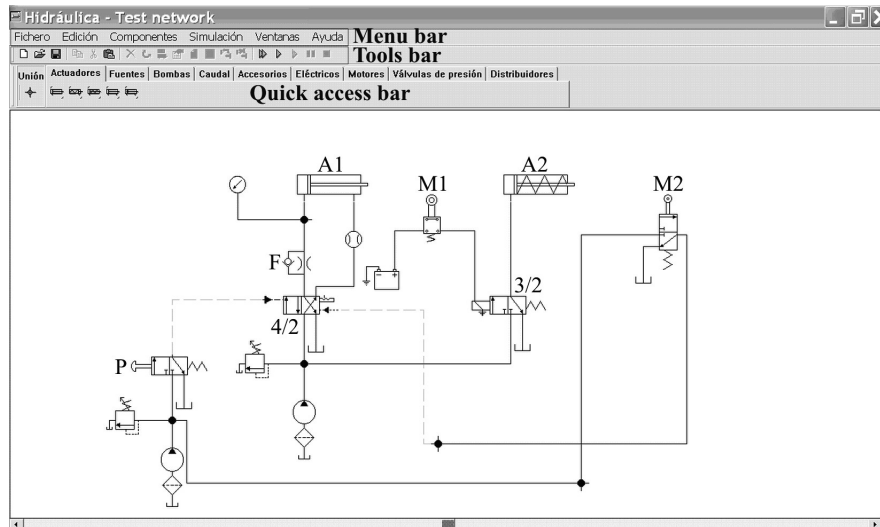
Fig. 5. General appearance of the user interface showing a sample network.

force balance, as indicated in Fig. 4; this is used to calculate the pressure at pump nodes. The magnitude of the corrected flow rate at each pump node can be derived from the node pressure and loss constants of the pump. This corrected flow rate is used to calculate the new pressure magnitude and flow rate at the exit of the pumps in a subsequent iteration. The indicated procedure is repeated until convergence is achieved at all network nodes (i.e. the difference in flow rate and pressure at pump nodes between two consecutive iterations is less than a predetermined error ϵ).

The real flow rate and pressure at each pump node is already known at the beginning of Phase 2. Signals taking the magnitude of these node variables are generated, transmitted and modified across the network following the same paths of the previous phase but without using the second loop (i.e. there is no flow return from closing figures to pumps). Phase 2 performs the calculations needed to obtain the remaining network parameters as, for instance, the shaft velocity of the actuators (see Fig. 4).

The configuration of the network can be modified during the simulation (for example, if the position of a directional control valve is changed). This may cause a link to remain pressurized even without actually being connected to a pump. Phase 3 checks the network for pressurized links that are not connected to pumps: if one of these links is found, then the software searches for an exit path (i.e. a link to a tank). In consequence, this phase begins at the tanks that were not previously simulated and performs the proper calculations to allow the discharge of the fluid if necessary.

The simulation process goes through an additional Sampling Phase once all the network parameters are known. The main purpose of this phase is to: (1) refresh the position of animated figures; (2) update the magnitude of the on-screen parameters shown; and (3) store the data needed to generate a final report. A simulation cycle ends

when a network figure performs an action that changes the magnitude of any parameter (for example, if the position of a directional control valve is modified). A new cycle is started automatically through Phases 1–3 plus Sampling Phase in a continuous simulation; in contrast, step-by-step simulations wait for the interaction of the user to start a new cycle.

3. THE USER INTERFACE

The interface of the application is Windows-based (see Fig. 5), showing a typical main menu bar and a tools bar. In addition, it provides quick access to a set of basic hydraulic elements (pumps, motors, actuators, control valves, etc.) and several electric components (solenoids, batteries, electric sensors, etc.) organized in component palettes. Hydraulic networks can be created by choosing the appropriate elements from these palettes. The elements are dragged and dropped in the workspace of the application and subsequently linked to set up the network. The default properties of the hydraulic elements can be modified by means of pop-up menus. Although there is also a palette for directional control valves, they can be designed on-the-fly through a specific input dialogue box, as shown in Fig. 6.

A sample network that was created using the application is presented in Fig. 5. The start push-button P activates the parallel flow position of the 4/2 valve thus allowing the fluid to enter into the left chamber of actuator A1. The roller of the mechanical control valve M1 is activated by the shaft of this actuator when it reaches its top position which, in turn, activates the solenoid of the 3/2 valve. The change in position of this valve forces the fluid to flow towards the chamber of the second actuator A2. The shaft of this actuator starts moving to the right until it reaches the
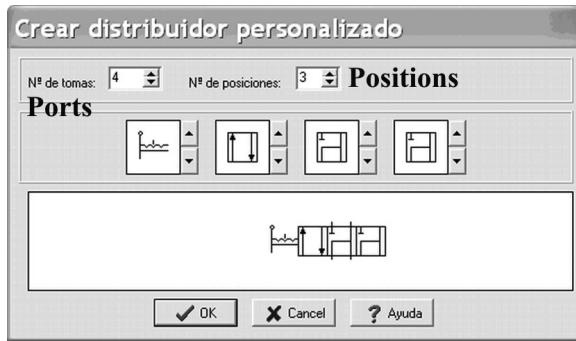
Fig. 6. Input dialogue box for user-designed directional control valves.

roller of the second mechanical control valve M2. When activated, this valve modifies the position of the 4/2 control valve to cross-flow, thus changing the fluid flow towards the right chamber of actuator A1; the backward velocity of the shaft is regulated by means of the flow control valve F. At the same time, the 3/2 valve returns to its neutral position so that the fluid in the chamber of actuator A2 is discharged to tank.

The integrity of the network can be checked before starting the simulation to prevent open-ended links or incompatibilities between components. If no problems are detected, then the simulation process is ready to be started. The simulations can be performed either in continuous or step-by-step mode. The user can start each new simulation step using the mouse. Also, it is possible to change the state of the network elements during the simulation (for example, the position of direc-tional control valves) thus permitting in-simulation interactions.

Pressurized links are shown emphasized when the simulation is in progress to help the students understand the operation of the network. Relevant physical magnitudes are printed on-screen, as observed in Fig. 7. This figure shows a frame of the double acting cylinder motion; as seen, the real position of the shaft and its velocity can be checked on-screen. Also, the network of Fig. 7 incorporates some instrumentation: a manometer to obtain the pressure in the left chamber of the actuator and a flowmeter to measure the flow rate coming from its right chamber.

Summary reports including the magnitude of the flow rate, pressure and velocity of selected network elements can be generated numerically or graphi-cally at the end of the simulation. The time evolution of the shaft velocity of the double acting cylinder is shown in Fig. 8 as an example of one graphical report. Additionally, the user can search for information about hydraulic elements in a help library that offers a brief theoretical and practical description of the components available in the application. The description of the hydraulic actuators is shown in Fig. 9 as an example of the information provided in the library.

4. THE EXPERIENCE WITH THE STUDENTS

The simulation software is used to complement the traditional laboratory practice in an on-line
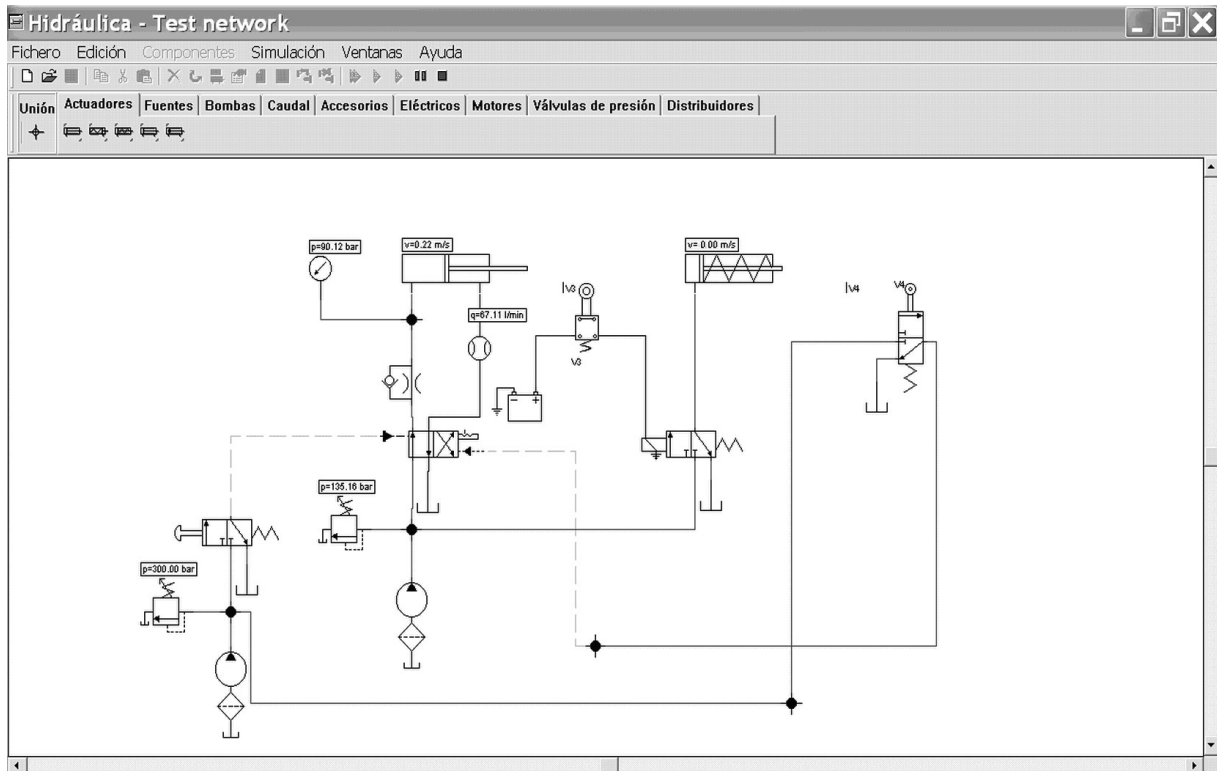

Fig. 7. Frame of the network animation showing the magnitude of relevant parameters.
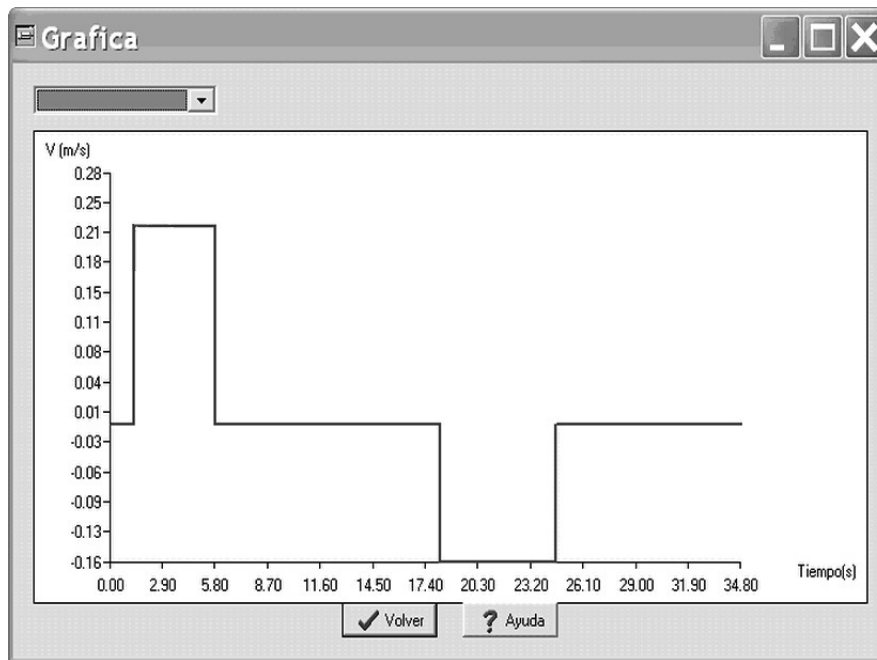
Fig. 8. Graphical report showing the time evolution of the shaft velocity of cylinder A1.

Fig. 9. Description of the hydraulic actuators in the help library. Top: Name of the element selected in the pull-down menu. Left: Picture and schematic symbol. Right: Description and principle of operation of the element.

subject on power hydraulics. The subject is taught in a bachelor degree in Mechanical Engineering. The average number of students studying the subject is about 40. Hands-on laboratory experience is arranged in a guided session of two hours. The students learn the practical basis of power hydraulics during the session through the implementation and analysis of a few sample circuits. Next, they can download the software to work autonomously and carry on with (virtual) laboratory practice using their own personal computers.

The application is downloaded by the students from the web of the subject. Only four files are required to run it: a pre-compiled executable and three DLLs that contain the drawings of the available hydraulic elements. Also, the students are provided with a user manual to help them to use the program. Several problems that deal with the design and calculation of more complex networks than those implemented in the laboratory are proposed during the course. The students use the application to design the networks, calculate the most significant parameters, and also to test and understand their operation.
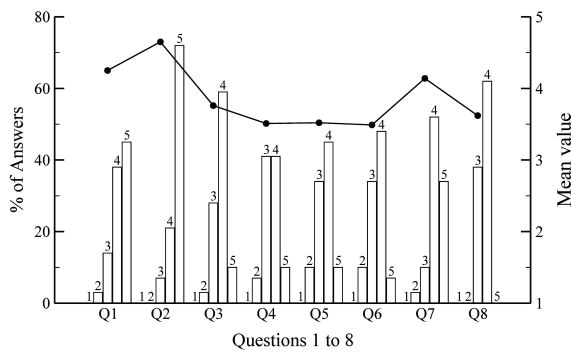
Fig. 10. Results of the opinion survey (see Appendix).

The effectiveness of the use of the software in the learning process was assessed at the end of the course by means of an electronic survey that was given to the students. The survey (see Appendix) was designed to obtain the opinion of the students about the application and, additionally, to ask for suggestions that could help in improving the program. The results of the survey, answered by 71% of the students, are presented in Fig. 10. The left y-axis shows the percentage of students that chose each option; the right y-axis presents the mean value obtained in each question. A numerical scale ranging from 1 to 5 was used, as shown in the Appendix.

The first question of the survey was made in order to ascertain whether the students had or had not had previous experience with computers. It is seen in Fig. 10 that about 83% of them were regular users of personal computers. The second question shows that most of the students (above 90%) said that the download and run of the application in their home PCs was very easy. The user interface (third question) was considered friendly by about 69% of the students; additionally, almost 28% of them expressed a neutral opinion, thus indicating that this is a feature of the application that should be improved in the future. Question four shows that a reasonable or a little time was required by about 82% of the students to learn to use the program. The results obtained in the fifth question show that more than 50% of the students said that the application was useful in improving their understanding of hydraulic networks. Also, about 34% of them state that the program helped but without being really useful; this indicates that the teaching techniques should be improved in the future when working with the application. With regard to the means of simulation available in the program (question six), about 60% of the students think that they are acceptable. The answers to the seventh question show an encouraging result: about 90% of the students prefer using specific software developed for a particular subject rather than generic

commercial programs. The application got an average mark of 3.6 (more precisely, of 3 from 38% of the students and of 4 from 62% of them).

The students were also encouraged to express their personal opinion about the application and to suggest improvements at the end of the survey. Some of the comments left are shown below:

- 'It would be useful to implement a tools bar of recently used elements.'
- 'I miss more variety of electrical apparatus.'
- 'A tool to turn the schematic of the network into a 3D drawing will be welcomed.'
- 'I think this program will be useful even for professional use.'

5. CONCLUSIONS

This paper presented a Windows-based educational software that was designed to simulate hydraulic power networks. It acts as a virtual lab that helps the students to understand the operation of complex or dangerous networks that would be difficult to set up in a laboratory facility. The application was implemented through object-oriented programming and it was conceived as a general simulation engine particularized for power hydraulics.

Hydraulic networks can be implemented by selecting the appropriate elements from several component palettes. The elements are put in the workspace of the application by means of a typical drag-and-drop routine and they can be subsequently linked. The default properties of each element can be modified through specific dialogue boxes. The simulation of the network can be performed either in continuous or in step-by-step mode also allowing in-simulation interactions. Numerical and graphical summary reports showing the time evolution of significant parameters can be generated at the end of the simulation.

The application was assessed by means of an electronic survey completed by the students. The results of this survey show that the user interface was considered friendly by most of the students and, additionally, that they required a reasonable time to learn to use the program. More than half of the students state that the application helped them to improve their understanding of the operation of complex networks. A significant conclusion from the survey is that about 90% of the students prefer specific software developed for a particular subject rather than commercial generic programs.

REFERENCES

1. J. González and R. Wagenaar (Eds.), *Tuning Educational Structures in Europe*, Final Report, Deusto and Groningen Universities, Deusto, 2003.
2. Accreditation Board for Engineering and Technology, *Criteria for Accrediting Engineering Programs*, ABET Inc., Baltimore, 2008.
3. J. Bourne, D. Harris and F. Mayadas, Online engineering education: learning anywhere, anytime, *Journal of Engineering Education*, **94**(1), 2005, pp. 131–146.
4. J. Hashemi, N. Chandrashekar and E. E. Anderson, Design and development of an interactive Web-based environment for measurement of hardness in metals: A distance learning tool, *International Journal of Engineering Education*, **22**(5), 2006, pp. 993–1002.
5. C. Yen and W. J. Li, Web-based learning and instruction support system for pneumatics, *Computers & Education*, **41**(2), 2003, pp. 107–120.
6. I. Gustavsson, A remote access laboratory for electrical circuit experiments, *International Journal of Engineering Education*, **19**(3), 2003, pp. 409–419.
7. A. Almendra, F. J. Jiménez-Leube, C. González and J. Sanz-Maudes, An experience de-localizing a freshman electrical engineering laboratory, *International Journal of Engineering Education*, **20**(2), 2004, pp. 170–175.
8. B. B. Ramos, J. V. Peláez, E. M. García and J. C. Ruiz, Design, navigation, and structure of a hypermedia application for the teaching—learning of pneumatic engineering design drawing, *Computer Applications in Engineering Education*, **15**(3), 2007, pp. 248–259.
9. V. Hlupic, Simulation software: users' requirements, *Computers & Industrial Engineering*, **37**(1), 1999, pp. 185–188.
10. T. C. Hung, S. K. Wang, S. W. Tai and C. T. Hung, An innovative improvement of engineering learning system using computational fluid dynamics concept, *Computers & Education*, **48**(1), 2007, pp. 44–58.
11. T. Wong, P. Biagras and D. Cervera, A software application for visualizing and understanding hydraulic and pneumatic networks, *Computer Applications in Engineering Education*, **13**(3), 2005, pp. 169–180.
12. Y. Zhou, J. J. Jiang and S. C. Fan, A LabVIEW-based, interactive virtual laboratory for electronic engineering education, *International Journal of Engineering Education*, **21**(1), 2005, pp. 94–102.
13. B. Duan, K. V. Ling, H. Mir, M. Hosseini and R. K. L. Gay, An online laboratory framework for control engineering courses, *International Journal of Engineering Education*, **21**(6), 2005, pp. 1068–1075.
14. J. Noguez and L. E. Sucar, Intelligent virtual laboratory and project-oriented learning for teaching mobile robotics, *International Journal of Engineering Education*, **22**(4), 2006, pp. 743–757.
15. R. Anton, H. Jonsson, J. C. Ramos, T. Gómez-Acebo and A. Rivas, Refrigerating Cycle Simulator: System Modelling, Educational Implementation and Assessment, *International Journal of Engineering Education*, **25**(2), 2009, pp. 261–271.
16. L. D. Feisel and A. J. Rosa, The role of the laboratory in undergraduate engineering education, *Journal of Engineering Education*, **94**(1), 2005, pp. 121–130.
17. J. O. Campbell, J. Bourne, P. Mosterman and A. J. Brodersen, The effectiveness of learning simulations for electronic laboratories, *Journal of Engineering Education*, **91**(1), 2002, pp. 81–87.
18. B. M. Olds, B. M. Moskal and R. L. Miller, Assessment in engineering education: evolution, approaches and future collaborations, *Journal of Engineering Education*, **94**(1), 2005, pp. 13–25.
19. R. P. Lambeck, *Hydraulic Pumps and Motors*, Marcel Dekker, New York, 1983.
20. M. J. Pinches and J. G. Ashby, *Power Hydraulics*, Cambridge University Press, Cambridge, 1989.

APPENDIX: OPINION SURVEY

Degree of agreement
$\rightarrow$

	1	2	3	4	5

Q1. I am a regular user of personal computers and general purpose programs (word processors, spreadsheets, etc.).

Q2. The download and run of the application on my own PC was easy.

Q3. The user interface is friendly.

Q4. A little or reasonable time is required to learn how to use the application.

Q5. The application was useful to improve my understanding of power hydraulics.

Q6. The means of simulation provided are adequate.

Q7. I prefer specific software developed for a particular subject rather than commercial generic programs.

Q8. I give a mark to the application of:

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