An electronic instrumentation course for non-electronic engineering students

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Abstract This paper reports on the implementation of a required course on electronic instrumentation for informatics engineering students. These students had proved in previous years to require a special approach, as their motivation for this subject was low. The course focuses on the basic concepts of Electronic Instrumentation, including analogue-to-digital and digital-to-analogue conversion and introducing the concept of instrument control. The course was organised in a set of lectures coupled with laboratory experiments, and a small project. To foster collaborative learning all the students work on the same laboratory experiments, simultaneously, organised in groups of two. The students' feedback on the course was more positive than in previous years, although not substantially so in terms of results. We feel that a change of attitude took place effectively, and that this could be attributed to the laboratory experiments using LabVIEW.

Keywords analogue-to-digital conversion; collaborative learning; electronic instrumentation; engineering education; LabVIEW

Electronic instrumentation courses are usually present in electronic engineering or similar degrees. However, the horizontal interaction with other engineering fields and the general use of electronic instruments often requires the introduction of such courses for non-electrical engineering degrees, such as in mechanical, civil, and informatics engineering. There are several engineering application fields that illustrate the impact of, or the interaction with electronic instrumentation. For example, in civil engineering transducers are commonly used in the stress analysis of buildings using measuring chains with complex networks of strain gauges. These are also often used in mechanical engineering for sensing strain in mechanical structures submitted to any kind of stress. The interaction with an immense number of analogue signals, and corresponding conversion to digital formats makes the computers widely used in processing digital data, intervening in various phases of data storage, processing and visualization. Thus, an informatics engineer plays an important role in conceiving and implementing the tools needed for the various data handling and processing tasks.

The course presented here was a required subject in an informatics engineering degree. However, the main concept can easily be applied to other non-electrical/ electronics engineering degrees. In this course we focused on the following topics: measurement and measurement errors; measurement methods and instrumentation; signals and signal conditioning; principles of current and voltage measurement; digital instrumentation; oscilloscopes; time and frequency measurement; transducers and measuring chains. The course contents are discussed in more detail below under the heading Course contents. The course was organised into three hours of lectures and one hour of tutoring per week, postulated on a classic teaching approach. Students proved unreceptive to and unmotivated by the subject in the first few years of the course. A move to a larger facility with more laboratory areas meant that a different approach could be taken to improve student performance.

We feel strongly that laboratory work is an important component of the formation of engineering students. As Edward[4] has put it: 'well-designed (laboratory) work may be the cement that binds curriculum together and may make an invaluable contribution to the engineer's professionalisation'. We therefore based our approach on the premise that a good set of laboratory experiments using some computer interaction tightly coupled with concise lectures would be more motivating to the students. Since the overall length of classes could not be changed, the one hour of tutoring each week was changed into a two-hour laboratory session every two weeks. Simultaneously, the three hours of lectures per week were used for a more concise presentation of the subjects in a two-hour session combined with one hour of tutoring, consisting mainly of problem solving on the blackboard. The course objectives and teaching methodologies are presented in the following two sections respectively. A set of laboratory experiments was conceived, based on a standard electronic bench consisting of a signal generator, analogue oscilloscope, frequency counter, multimeter and a PC equipped with a data acquisition (DAQ) card. The timing and subject of the experiments were designed to afford a good synchronisation with the lectures. This was mostly a matter of scheduling and is commented on in more detail in the section on Teaching methodology. In the sub-section headed Laboratory experiments we present the set of four laboratory experiments that were developed for this course, covering fundamental concepts, basic principles of measurement, analogue-to-digital conversion, signal acquisition and a final work which gathers all these aspects and introduces the concept of instrument control. A course website (www.fe.up.pt/~campilho/IE) provides access to learning materials such as handouts, computer programs and laboratory work guides. E-mail is used to enhance out-of-classroom communication between students and instructors.

As some authors advocate[4] we gradually delegate the control of the experiments to the students. Starting by close control, where the students have to follow well-defined instructions, we end up with open answers and methodologies. As this course usually appears during the first years of the degree, we keep the objectives for each experiment well defined.

An important factor in the success of this course was the use of LabVIEW[1] in the laboratory experiments. Incidentally, we found out that it is also quite useful to the instructor in the preparation of lecture materials. LabVIEW is a software development environment that uses a graphical language to create 'Virtual instruments' (programs) and to interact with DAQ boards and other peripherals and instruments. It is a powerful tool that is easily assimilated by the students, attracts their interest, and allows for a good interaction and rapid knowledge acquisition of measurement methodologies, thus providing an increase of learning efficiency. LabVIEW has been used by different authors in setting up laboratory experiments. Consonni *et al.*[2]

present an approach to teach basic electricity and electronics to undergraduate students of an electrical engineering degree. LabVIEW provides the communication between computer and instruments and was used in the design of graphical and calculation routines. The authors present several examples, namely for measuring frequency, for controlling a digital oscilloscope, for modelling inductors, among others. Goulart *et al.*[3] also illustrate the use of LabVIEW for creating a virtual instrument for measuring electrical three-phase power components. Jiménez-Leube *et al.*[5] describe an approach using computers to guide and supervise laboratory work in an electrical measurement laboratory, with software developed by the authors, and structured in the form of an electronic book.

Course objectives

The *Electronic Instrumentation* course presented here is an undergraduate course, taken by informatics and computation engineering students. It was conceived to allow attendance by students without an electronics background. It could therefore be used in other non-electronic engineering courses, or expanded into a first course in this subject in an electrical/electronics engineering degree. The objectives include the presentation of fundamental measurement concepts and measurement methodologies including the description of basic instruments that are the technological implementation of general methodologies. Moreover, we felt that a hands-on approach would be instrumental in attaining other objectives, such as an increase in student motivation and learning effectiveness, by increasing the students' confidence level in their ability to solve specific problems. The laboratory applications presented in the sub-section headed Laboratory experiments can be tuned according to the degree where the course is inserted. This means that students of informatics engineering may be oriented towards the design of virtual instruments, which was the case here. For example, students of mechanical engineering could focus on the acquisition and processing of mechanical quantities measured by specific transducers. Following the above reasons, the global objectives stated for the course were:

- To review the fundamental concepts and methodologies of measurements and measuring instruments
- To study measurement methods and their application to real problems, possibly in several application domains according to the student's degree
- To illustrate the basic concepts in the laboratory and experiment with different measurement methods
- To provide an introduction to LabVIEW and to virtual instrument creation

The specific objectives can also be tuned according to the students engineering degree, namely electrical, electronics, mechanical or informatics degrees.

Teaching methodology

There are several challenging and conflicting issues in setting up a course where methods and applications are both the focus of attention. An applications-oriented course runs the risk of being a set of recipes only useful for the specific application. A methodologically oriented approach may suffer from being too abstract and general.

Another challenge, in an introductory course, is facilitating teamwork, group discussions, criticism and learning among participants.

To meet these challenges, we followed a combined methodological/application approach to the course. The material of the course is to be presented from a methodological point of view with illustrations on different concepts, measurement methodologies and measurement applications.

This methodological/application approach is pursued using lectures and laboratory experiments. These elements are designed and sequenced in a way that fosters participation and feedback from the students. The lectures are organised in a traditional way, using transparencies for description of the methodologies, frequently illustrated with virtual instruments produced with LabVIEW. The topics of the labs were chosen in order to facilitate the learning process, to integrate theoretical knowledge with experimental work, and to encourage student participation in the lectures. The schedule of lectures and laboratory sessions was arranged in a way that allowed the fundamental concepts and methodologies required by lab work to be broadly covered during the lectures. After the subjects were covered in the lectures, all students had their laboratory session in the same week. The lecturers, i.e. the authors, provided lab supervision. This gave the possibility of calling the students' attention to the points covered in the lectures that are being illustrated by a particular experiment. Thus, the teaching and learning cycles are linked in such a way that the labs appear as a core for illustration of the methodologies.

Course organisation

The course was organised in a set of lectures and laboratory experiments. The challenging component was the organisation of a balanced and harmonious programme of laboratory work. This must provide an increasing learning capability of electronic instrumentation techniques by experiencing, by observing the sensitivity of the results to the selection of parameters and by comparing the performance of different methods. Furthermore, it must give the students some knowledge of the capabilities of LabVIEW. The following paragraphs give some insights on the different components of this course.

Course contents

The fundamental concepts and methodologies of electronic instrumentation are covered in this course, as briefly outlined below. It closely follows the textbook[6] of one of the authors of this paper. The main topics covered in the course are the following:

1. *Measurement and measurement errors* – definition of the most important concepts associated with metrology together with the study of measurement errors and measurement uncertainties.

2. *Measurement methods and instrumentation* – brief overview of main measurement methods and global static and dynamic characteristics of electronic instrumentation.
3. *Signal and signal conditioning* – definition of the main signal characteristics and signal conditioning methods, such as attenuators, amplifiers and basic filters.
4. *Principles of measurement of electrical current and voltage* – description of the main detection methods for measuring electrical current and voltage.
5. *Digital instrumentation* – in this chapter special attention is given to analogue-to-digital and digital-to-analogue conversion principles; basic organization of a digital multimeter is also presented.
6. *Oscilloscopes* – analogue and digital oscilloscopes, together with measurement principles are studied under this topic; the instrument operating principles and the user perspective are taught simultaneously.
7. *Digital counters* – time and frequency measurements using digital counters are studied; the measurement errors introduced by this type of instruments are analysed and the ways to minimize the errors are presented and illustrated using different situations.
8. *Transducers and measuring chains* – this chapter studies the measurement of various physical quantities and the organization of a measuring chain formed by a transducer, a conditioning circuit, and an A/D converter. Various measurement examples are given and the measurement errors are estimated.

Laboratory experiments

Exposure to real practice, providing the application of theoretical knowledge, is offered to the students through a set of laboratory experiments. In this section we present a set of four laboratory experiments, based on LabVIEW, illustrating basic principles of measurement, analogue-to-digital conversion, signal acquisition and simple automated testing with instrument control. We introduce the basic concepts of LabVIEW in a two-hour classroom session using a PC with video projection. The students then learn LabVIEW by first examining how the experiments are put together, and finally creating a program of their own, using as building blocks some parts of the previous programs. The laboratory work guides were given to the students one week in advance, and the students were expected to prepare for the lab session in advance, by reviewing the relevant theoretical concepts. One possibility that was not explored in the year that we are reporting on, but which we are experimenting with now, was the inclusion in the work guides of questions on the theory underlying the experiment, which the students must answer before the lab session. All the students in each laboratory session, organised in groups of two, do the experiments simultaneously, and all the class does the same experiment in the same week. In our experience, a set of common laboratory experiments is a good way to foster interaction among the students, stimulating teamwork and collaborative learning. The experiments are structured in such a manner that control of the experiment is transferred gradually to the students. The first experiment is strictly defined, the students being asked to follow the instructions closely. Control is gradually relaxed in the next experiments. To this end, we found the LabVIEW programmes (VIs) to be a powerful exploration tool. For example, the second assignment allows students to investigate the consequences of quantisation in A/D conversion, with different signal amplitudes, different signal waveforms (in a more recent version of this we added a noise waveform), and varying the signal phase. In the last assignment the students are asked to design a more complex virtual instrument, without being closely guided throughout the project. In this last assignment, the students use concepts and programmes from the previous assignments, as explained below. The first three experiments have a duration of two hours while the fourth is structured in two periods of two hours, the week in between being used to analyse the results obtained in the first part and to study the work to be implemented in the second part. The stated objectives for each one of the laboratory experiments were (the unstated objective was that the students learn LabVIEW by doing):

- *Signal generation and measurement* – the main objective of this laboratory experiment is to illustrate the concepts of average and r.m.s. values of signals, with superimposed noise and a d.c. component.
- *Analogue-to-digital conversion* – sampling and quantisation, as the main principles of this operation, are illustrated with this experiment, giving special attention to the aliasing and quantisation effects.
- *Signal acquisition* – the goal of this experiment is to give the students the first contact with a data acquisition board, acquiring various analogue waveforms of different frequency and in a range of amplitudes starting from a few millivolts. With this introductory experiment, directly connected with the acquisition card, the students are able to illustrate the effect of the sampling frequency, aliasing and noise using 'real' signals.
- *Automated test system for measuring the frequency response of a linear circuit* – the goal of this experiment is to design a system for measuring the frequency response of an RC circuit. For this purpose the students need to program a function generator for outputting a modulated sinusoidal waveform, acquire the input and output signals with the data acquisition card, and process the signals to obtain the frequency response of the circuit. This is the more ambitious experiment, taking two sessions (4 hours), where we delegate control of the work to the student. This work also introduces the concept of instrument control.

The nature of these objectives is twofold: technical and pedagogical. The students are gradually introduced to the measurement methods using virtual instruments, by guided experimentation using pre-stored data, or mathematically defined functions. This happens in the first two experiments. The other experiments involve the use of other instruments, connected through a data acquisition board and a communication link. In the following paragraph we give more details of each one of the four experiments.

Signal generation and measuring

A virtual instrument is provided to the students for signal generation and measurement of sinusoidal signals in the presence of noise. The corresponding front panel is presented in Fig. 1. The users can control the amplitude and d.c. value of the sinu-

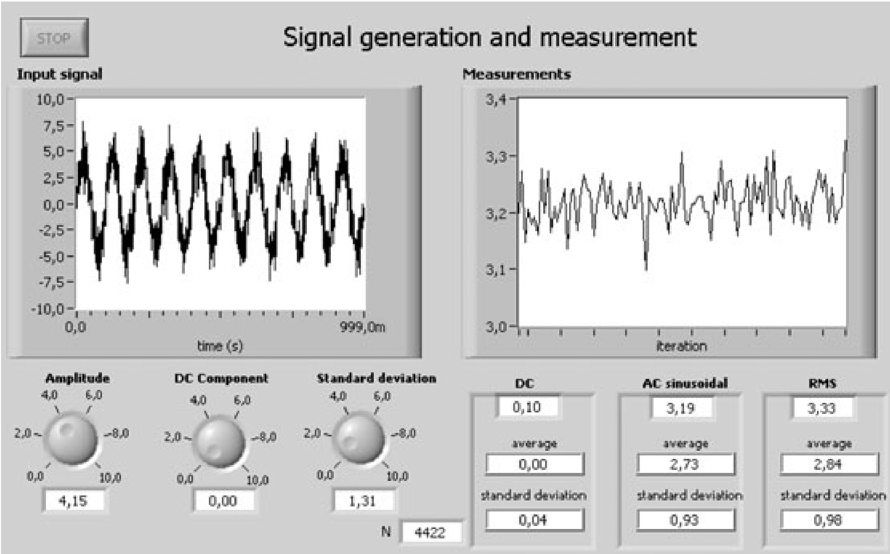

Fig. 1 *Virtual instrument front panel for signal generation and measuring. The graph on the left represents the input signal, and the graph on the right represents the evolution of the r.m.s. value in a sequence of measurements.*

soidal waveform, together with the standard deviation of the additive noise introduced in the signal. Several measurements are made, to illustrate the influence of noise on the uncertainty of the result.

The measurements are averaged during a pre-specified integration time and iterated along a number of iterations N. Evolution of the measurements is represented in the front panel, as illustrated in Fig. 1 for the r.m.s. value. Measurement results are also represented, namely the measurement value obtained in the last iteration, together with the average and standard deviation estimated over the number of iterations N. The following parameters are measured:

- *D.c. value* V_0 – this is the average value of the input signal $v(t)$ measured during a pre-specified integration time, T:

$$V_0 = \frac{1}{T}\int v(t)dt$$

- *A.c. sinusoidal* V_{eff} – this is an estimation of the r.m.s. value for sinusoidal signals, obtained by averaging the full-rectified input signal and pos-multiplied by a constant $k = 1.11$:

$$V_{\text{ef}} = \frac{k}{T}\int |v(t)|dt$$

- *Root mean square voltage* V_{rms} – the true root mean square value of the input signal $v(t)$:

$$V_{\text{rms}} = \sqrt{\frac{1}{T}\int v^2(t)dt}$$

With this laboratory experiment, the student learns the fundamental concepts of measurement, averaging $v(t)$, $|v(t)|$ or $v^2(t)$, and its relations to important signal characteristics, together with the uncertainty of measurement associated with noise. This is also the first opportunity to learn the basics of LabVIEW.

Analogue-to-digital conversion

The main goal of this experiment is the illustration of the main concepts inherent to the analogue-to-digital conversion, namely sampling, aliasing and quantisation. In order to illustrate the quantisation effects, the relation between the input of the quantiser $v(t)$ and the corresponding output $v_q(t)$ is implemented by the expression

$$v_q(t) = Round\left(\frac{v(t) - V^-}{Q}\right) \quad \text{for} \quad v_q(t) \in \left[V^-, V^+ - Q/2\right]$$

The function *Round* returns the nearest integer. For a quantiser with n bits, having as maximum and minimum values V^+ and V^-, the quantum Q is given by

$$Q = \frac{V^+ - V^-}{2^n}$$

Figure 2 illustrates the front panel of the experiment, where the student has the possibility to study the quantisation effects for several input signals (sine, triangular, rectangular and sawtooth waveforms) and different number of bits. The quantiser has an input range from -2^7 to 2^7.

The input signal amplitude can be controlled within this range. The quantisation error $e(t)$ $[e(t) = v(t) - v_q(t)]$ is also plotted in the front panel, allowing the students to observe the error in relation to the original and quantised waveforms.

Another program, whose panel is shown in Fig. 3, is used to illustrate the aliasing phenomenon. When this program is running the students can modify the frequency of the sine wave that is fed into the sampler, and observe both the resulting reconstructed sine wave and its power spectrum. The sampling frequency is fixed at 1 kHz, a notional value since the waveform is synthesised in the program. The number of samples generated is fixed at one thousand, which is one second of 'time'. The frequency values are restricted to integer numbers to avoid the spectrum spreading effects of an input signal with a non-integer number of cycles (and to avoid introducing the concept of windowing).

Signal acquisition

In this experiment the data acquisition card is used to collect and display signal samples from one channel, under program control. The front panel of this virtual

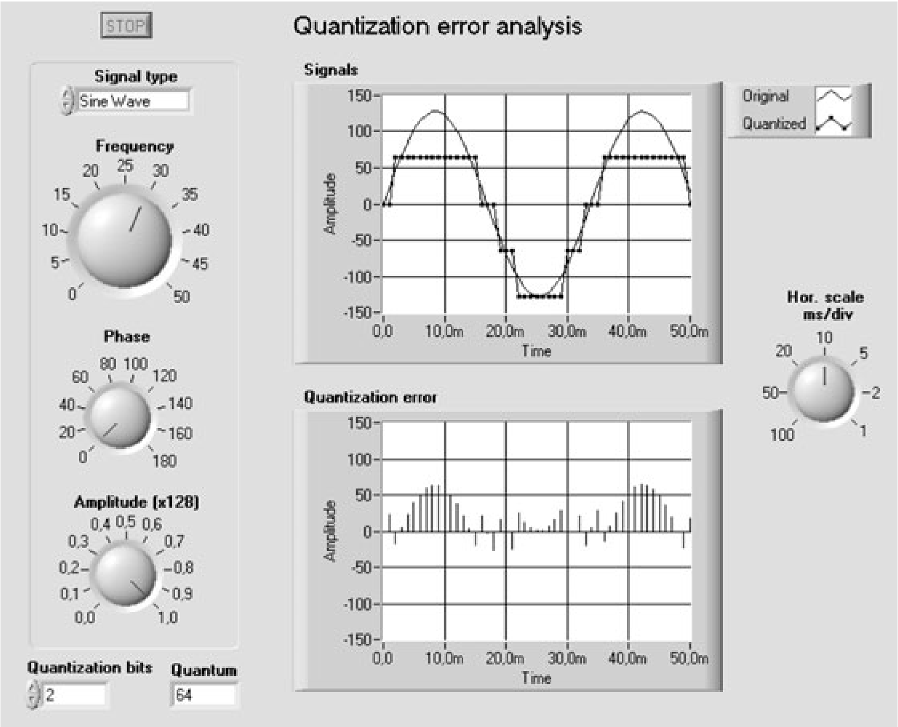

Fig. 2 *Analogue-to-digital conversion: quantisation.*

instrument is shown in Fig. 4. Here the student can configure the data acquisition card by selecting the channel, the channel gain, the number of samples to acquire and the sampling frequency. The samples are displayed in the graph, and the average and variance of the acquired samples are represented in the front panel. With this simple virtual instrument the students are asked to acquire signals ranging from low level (10 mV peak-to-peak is the suggested amplitude) to signals with amplitudes in the range of a few volts. Analysis of the variation of sampling frequency and number of samples is also suggested. Within this framework the students can observe the effect of noise, visible for the 10 mV signals, evaluate the effect of undersampling, induce aliasing, and find out what is the maximum speed at which the sampling can be done with this virtual instrument and the specific computer. The ensuing analysis highlights various and important problems of acquisition of analogue signals. The students are asked to elaborate around the topics of 'measurement in the presence of noise' and 'aliasing effects'.

The students are also asked to expand the virtual instrument to a multi-channel virtual instrument, and to determine the acquisition speed in this case of more than one channel.

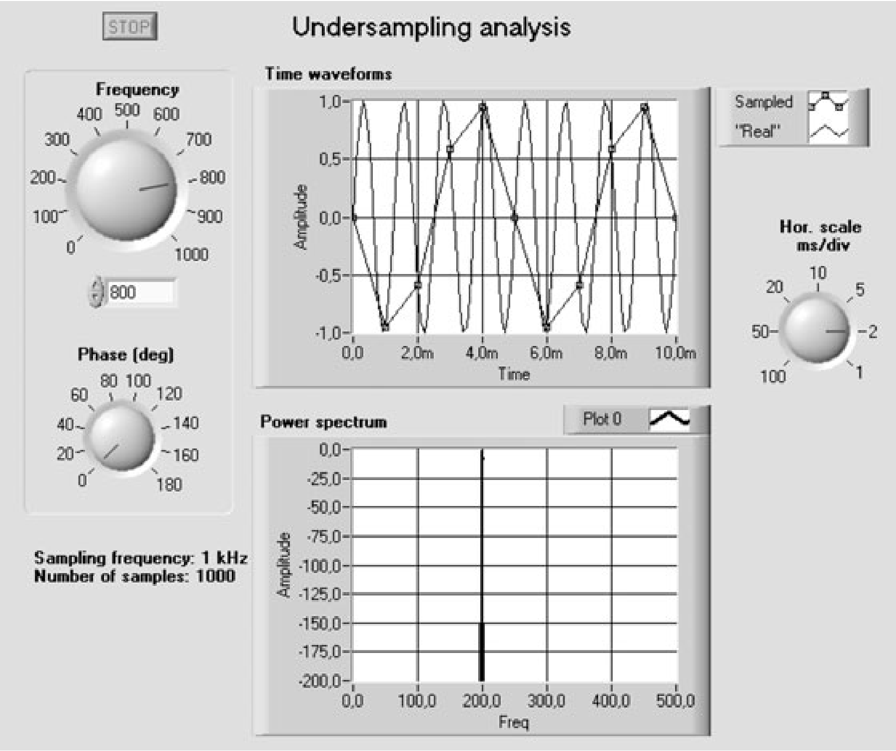

Fig. 3 *Analogue-to-digital conversion: undersampling.*

Automatic system for measuring the frequency response of an RC circuit
The main goal of this experiment is the analysis and design of an automatic system for measuring the frequency response of a linear circuit. The generation of frequency is controlled either by direct programming of the function generator, via a RS-232 connection, Fig. 5(a), or by inputting a linear ramp from the DAQ D/A converter, Fig. 5(b).

The students are given the first of these programs (controlling the generator via RS-232) and are told to try it out and analyse it. The students are then required to build the second program using as inspiration the first one, and also using parts of the VIs used in previous laboratory assignments (signal generation, data acquisition). The students' experience and knowledge from the previous experiments is thus capitalised upon in this assignment, as the students use concepts about signal measurement from the first assignment, and signal acquisition from the third assignment, as well as using portions of the VIs from these assignments.

Figure 6 shows the front panel of the virtual instrument illustrating the type of result that was obtained with the program given to the students.

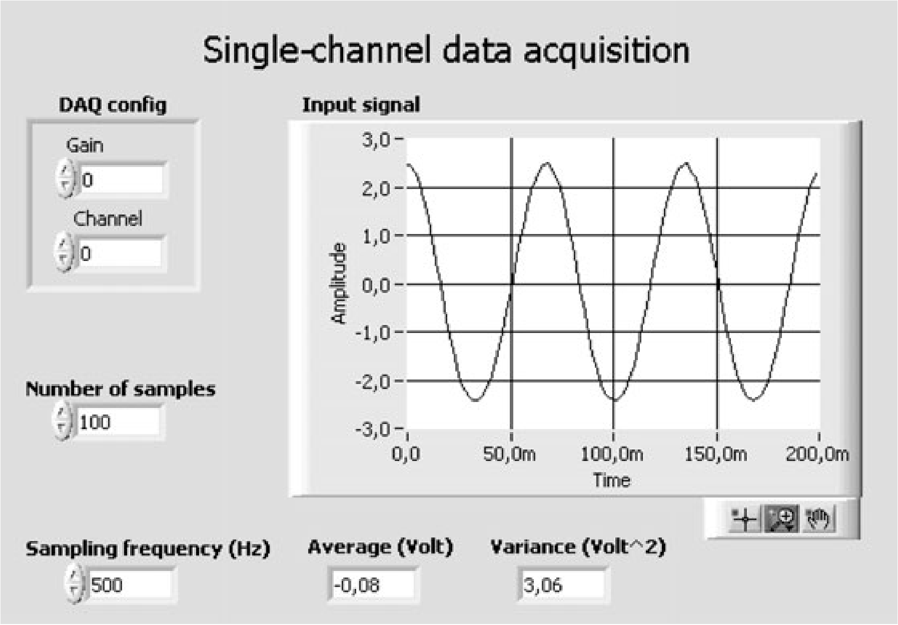

Fig. 4 *Signal acquisition experiment.*

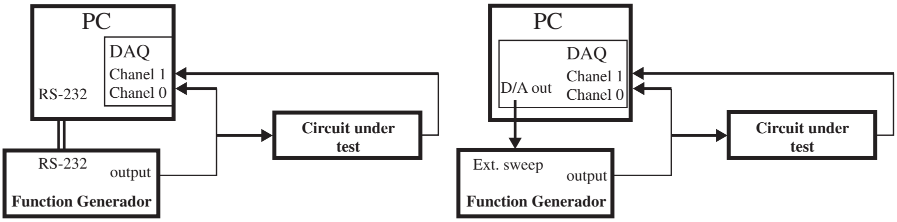

Fig. 5 *Bock diagram for measuring circuit frequency response: (a) controlling the function generator using RS-232; (b) applying a linear ramp into the external sweep control input.*

Discussion

We were faced with several important issues when organising this *Electronic Instrumentation* course within an engineering degree, at an undergraduate level. The most important was the lack of motivation of the non-electronics engineering students for a typical electronics engineering subject, despite the tailoring of the course contents that had already been introduced. We decided to maintain course depth and breadth and to try to motivate the students.

The decision to involve the students further in the subject, by capturing their interest with engaging laboratory experiments, closely coupled with lectures, seemed to

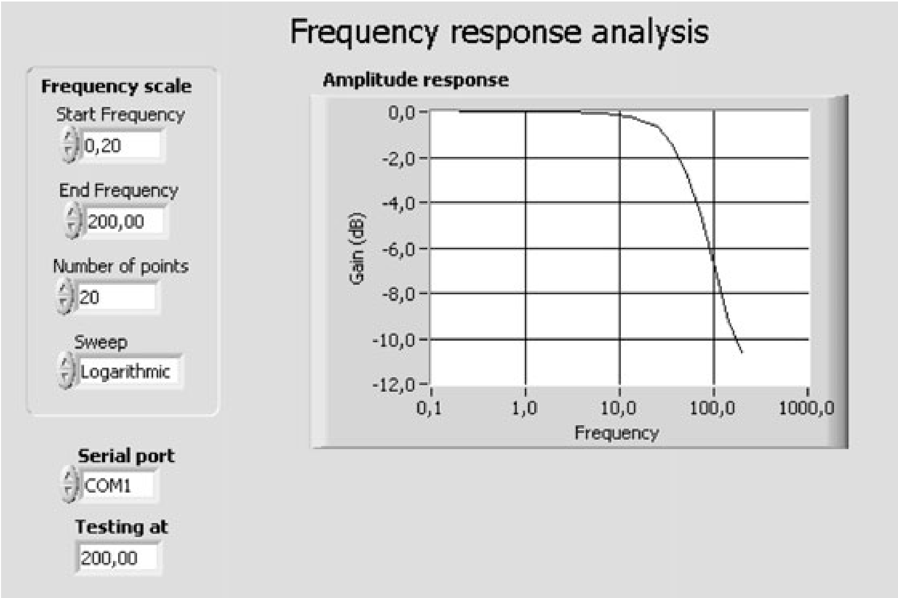

Fig. 6 *Frequency response of an RC circuit.*

be the right one: student commitment to the course increased, as indicated by the percentage of students attending the non-compulsory lectures, in marked increase over previous years. The students' interest and level of satisfaction with the course seemed greater, based on subjective evidence, namely students' reactions in the labs.

However, in consonance with other results[1], there was no significant effect on the percentage of pass grades (around 79%), or in the average passing grade. In order to interpret the passing and grading results, it would be necessary to gauge the amount of effort put in by the students to prepare for the final exam.

Responses in the student surveys, taken at the end of the semester, did not show a significant change from the previous year, including aspects such as the degree of difficulty, the amount of time and effort put into the course, coordination between lectures and practical work, which were all about even with the average for the course. Perhaps the only way to shed some light on these results would be to follow up on the survey with interviews, and in these try to clarify the meaning of the survey results.

In any case, since this is an engineering degree, we felt that it was very important that the students should be able to illustrate, and experiment on, the concepts and methodologies taught. In engineering, it does not make any sense to study electronics instrumentation without extensive experimentation, without assessing results, without evaluating the uncertainty of the results, without sensing the importance of noise. The laboratory work played an important role in learning by experimenting. It also provided a convenient means to promote and stimulate co-operation among students.

We think that giving the students room for experimenting without close guidance is important. In this course we were concerned with teaching introductory concepts on measurements, signal acquisition and so on, and the experiments that allow students to try out different parameters of an experiment are a powerful aid, in our opinion. A recurring situation during a lab experiment was a student trying out something and not understanding the result, calling the instructor and discussing with him what was happening, and finally reaching an understanding of the phenomenon.

We feel that the experience was a very positive one and that it will be useful in other contexts. During the next academic year we plan on expanding the course presented here, in order to apply the experience to electronics engineering students. We hope to be able to report on the results at a later stage.

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