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An Undergraduate Laboratory in Communication Fundamentals*

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An undergraduate course in Communication Theory, aimed at Spanish Telecommunication Engineering students, has been augmented with various experiments introduced to enrich the student's understanding on basic topics such as linear and angular modulations, random signals and noise. The equipment required is minimum and inexpensive. In fact, the equipment already available in lab benches of an Electronic Instrumentation course has been used with some additional inexpensive, off-the-shelf electronics. The full exploitation of the potentials of the existing instruments and their PC connectivity made additional investment unnecessary.

INTRODUCTION

HIGHER EDUCATION in Spain has experienced profound changes in the last two decades. A major reform occurred in 1983 with the so-called Law for the Reform of Universities (LRU), now replaced by the Organic Law of Universities (LOU). Concerning technical curricula, these changes tend to prepare students for an industrial and economic environment, trying to emphasise practical skills at earlier stages of the students' academic career.

The Public University of Navarra is relatively young (it was established in 1987) so that it has incorporated these changes more dynamically. One of the degrees offered to our students (since 1989) is Telecommunication Engineering. As in other Spanish universities, such degree is traditionally close in concept to Electrical Engineering degrees in Anglo-Saxon countries, yet with remarkable differences. In particular, emphasis is put on signal and systems theory, electronics, transmission media, computer architecture and networks, at the expense of topics closer to mechanical engineers, such as materials science and control theory. But certainly one of the main subjects treated is communication systems, both analogue and digital. The inclusion of various mandatory courses covering such topics is an implicit recognition of their relevance to the engineer's background. Concerning this fundamental subject, the renovated curricula in Telecommunication Engineering at the Public University of Navarra established a course entitled *Communication Theory* and designed for juniors that covers the main aspects of analogue communications as well as the fundamental aspects of random signals and noise. The prerequisites are a junior course on linear systems and a mathematics background including Fourier transforms, statistics, and vector calculus. Digital communication systems are treated in a coordinated fashion in another simultaneous course.

Traditionally, theoretical basis of communication systems has been introduced in most Spanish engineering curricula at sophomore or junior levels without a parallel lab experience providing a deeper grasp of the functioning of communication systems and the influence and characterisation of noise. 'Experimental' work is even identified in some cases by the students at these levels as canned problems solved on the board, usually readily derived from the theory presented and providing little additional insight. It has been the believe of the author that a carefully designed experimental approach simultaneous to the theoretical introduction of the fundamental topics on modulation and noise notably contributes to a more solid and founded student background, based on an earlier handling of 'real' signals and electronic instrumentation. This point is particularly evidenced in those aspects concerning random signals and noise, topics that in the author's teaching experience are difficult to assimilate by the students if just a theoretical approach is followed.

In this context, the author has developed a set of lab experiments that augment the course *Communication Theory*. They have been applied in the last three academic years, experiencing their contents an ongoing refinement and renovation during this time. The final result is described in this paper, basically consisting of three sets of lab experiments. The first one covers linear modulation, the second one angular modulation and the third one random signals and noise. One side objective of these lab experiments was the use of general-purpose equipment already available in most departments of electrical and computer engineering. Two obvious benefits of this approach are

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the avoidance of dedicated investments and the familiarity of the students with the lab bench acquired in former courses, thus saving time and allowing them to focus on the topics treated. In addition inexpensive, familiar components like a walkman radio are employed. This fact encourages students to see the technology with the everyday objects they can encounter. This approach is also followed by the successful materials science education program at the University of Pennsylvania, which uses a bicycle and a walkman as instructional aides [1]. It is also exploited at the undergraduate lab in magnetic recording at the Pittsburgh's Carnegie Mellon University [2], where a simple tape recording system is employed.

COURSE CONTEXT

The course on Communication Theory at the Public University of Navarra, in which the aforementioned lab experiments are introduced, has a total of 60 contact hours assigned. The main topics treated are:

1. Linear modulations and frequency multiplexing.
2. Angular modulations.
3. Random signals and noise.
4. Analogue pulse modulations, PCM and time multiplexing.
5. Information theory.

Although several topics are studied, the main core of the course is analogue modulations and noise in communications systems, which are studied at length. When the student faces this course, he or she has received a sound basis on signal and system theory (60 hours), statistics (60 hours), analogue and digital electronics (230 hours), as well as basic courses on mathematics and physics. Besides the lectures in the classroom, students have also attended various sessions in the laboratories, using typical low-cost instrumentation (analogue oscilloscopes, signal generators, etc.). Such former experience with the basic lab bench is therefore exploited, as mentioned before.

When the student completes the course, he or she should have a clear understanding on which modulation method best fits to a certain application, how it can be generated and detected and how noise influences signal transmission.

LAB BENCHES

These experiments employ lab benches already available in our department, formerly aimed at another course on Electronic Instrumentation described in [3]. Hence no additional investment is required. The equipment and components employed are inexpensive, and readily available in standard undergraduate laboratories of departments of electrical and computer engineering. This novel use of existing technology instead of the employment of dedicated, expensive and complex instruments is a theme considered as important in several undergraduate laboratory programs [4, 5].

The complete lab bench is shown in Fig. 1. Each station in the undergraduate lab is outfitted with the following items:

- PC Pentium II, 32 Mb RAM, 2 Gb HD
- IEEE-488 Interface (PCIIA card) and bus
- HP 33120A arbitrary signal generator
- PM 3335 analogue/digital oscilloscope
- DC power supply
- Breadboard and some discrete components (resistors, capacitors, op amps)
- Microphone
- Walkman (owned by the students)

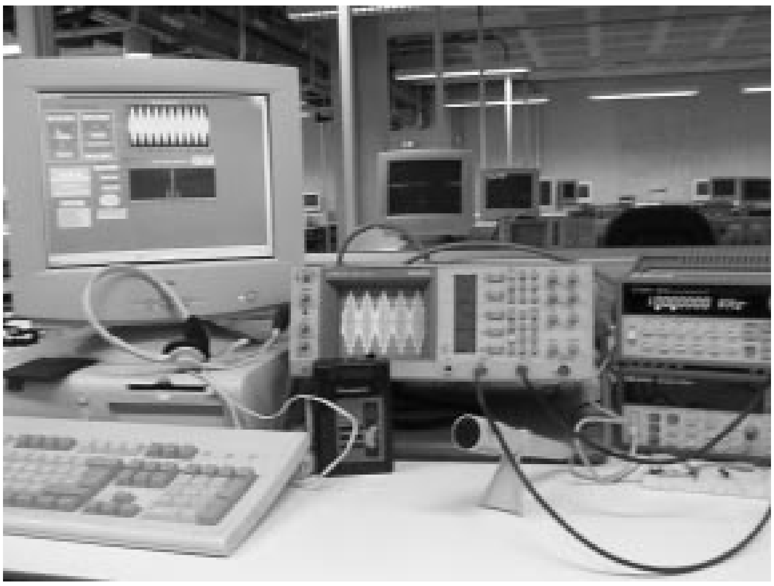

Fig. 1. Undergraduate lab bench employed.

All the instruments include an IEEE-488 interface. The signal generator provides several built-in signals ranging from periodic sine or square waves to AM or FM modulated waves, as well as Gaussian noise. The oscilloscope has a dual analogue and digital nature, providing the didactical advantage of a simple comparison between analogue and digital operating modes. Both instruments, connected to the PC through the IEEE-488 bus, lead to a great deal of flexibility at configuring the lab bench. In particular, they notably augment the measurement capability of the benches by creating through software a spectrum analyser and a network analyser, neither instruments being physically available in the lab bench. Dedicated software has been developed that configures, together with the connectivity hardware, the experimental lab bench. Such software was developed using LabView, but was finally produced as a standalone executable program, so that the LabView software is not required in the bench-top PCs. The lab bench also contains an HP 53121A Universal Counter and a National Instruments I/O card, LabPC+, which have not been employed in this course.

LINEAR MODULATIONS

The main objectives pursued in the first set of lab experiments are to illustrate the concept of linear modulations, by means of one of the most widely employed linear modulation schemes in commercial broadcasting, namely, amplitude modulation (AM). The student generates different AM modulation schemes by means of different modulating waves, and identifies the role of the modulation index. The close relationship between time and frequency representation of a modulated signal is emphasized. Moreover, based on the idea proposed in [6], a simple AM transmitter able to transmit in the commercial range from 535 kHz to 1605 kHz is built by the students, so that the resulting modulated signal can be detected by a simple AM radio receiver. Some practical issues of commercial AM broadcasting are reviewed during the experiments.

Figure 2 shows the main window of the program running on the PC for these experiments. The boxes at the upper left show a group of controls that remotely configure the modulated waveform generated by the signal generator, in those aspects such as modulating and carrier waveform shapes and frequencies, and modulation index. The program sends such settings to the signal generator through the IEEE-488 interface and bus. The upper right graph shows the modulated signal generated in the time domain. It is obtained by an almost continuous download of the data acquired by the oscilloscope through the IEEE-488 bus, when one of the oscilloscope inputs is connected to the signal generator output. A FFT is performed on these data, so that a representation of the waveform in the frequency domain is shown in the lower right graph of the screenshot, corresponding in particular to the amplitude spectrum.

The lab session begins by acquiring a simple sinusoid and relating its representation both in time and frequency domains. The differences with the theoretical spectrum (impulse or delta function) expected by the students allows the introduction of some important practical issues such as the truncation unavoidable in any acquisition of a non time-limited (e.g., periodic) signal, and the leakage effect inherent to the FFT. The need for acquiring many signal cycles to get a fair spectrum representation is readily derived in this context. Also the effect of different windows (rectangular, Hamming, Hanning, etc) on the FFT calculation is analyzed, and the advantages of logarithmic versus linear amplitude spectrum representation is assessed.

Once studied these effects, the students generate AM signals using different modulating waveforms (sinusoid, periodic square, periodic exponential, periodic ramp, noise, etc). The different spectra obtained are interpreted. A practical issue that is also highlighted is the convenience in AM of triggering the oscilloscope externally with the modulating wave (using the sync output of the signal generator as trigger source) so that the envelope remains fixed in the oscilloscope screen.

The next task is the measurement of the modulation index of an AM tone modulation, using the oscilloscope cursors. Then, the effect of varying the modulation index both in time and frequency representations is assessed, and the concept of overmodulation is reviewed. Similarly, the effects of varying the shape, amplitude and frequency of modulating and carrier waves both in time and frequency are subsequently analyzed.

Then, an AM transmitter is readily built by the students. The signal generator is employed as a transmitter, connecting a simple wire as a rudimentary antenna to its output. First, a 1 kHz tone modulation is generated with a carrier frequency in the AM broadcasting band not employed by local radio stations. The students tune their walkman to hear the modulating tone. The perceived tone and intensity are related to the modulating frequency and modulation index, respectively, of the AM modulation. The student is encouraged to determine the highest modulating frequency that he or she can hear at the walkman headphones, knowing that the maximum audible frequency is typically 17–20 kHz depending on age, working environment, etc. Most students suddenly feel that they suffer from premature deafness, until the effect of the receiver post-detection low-pass filtering is revealed. Concerning sound intensity, the student is invited to move around the lab to see the effect of the modulation index on the coverage of the transmission.

After these experiments with tone modulation,

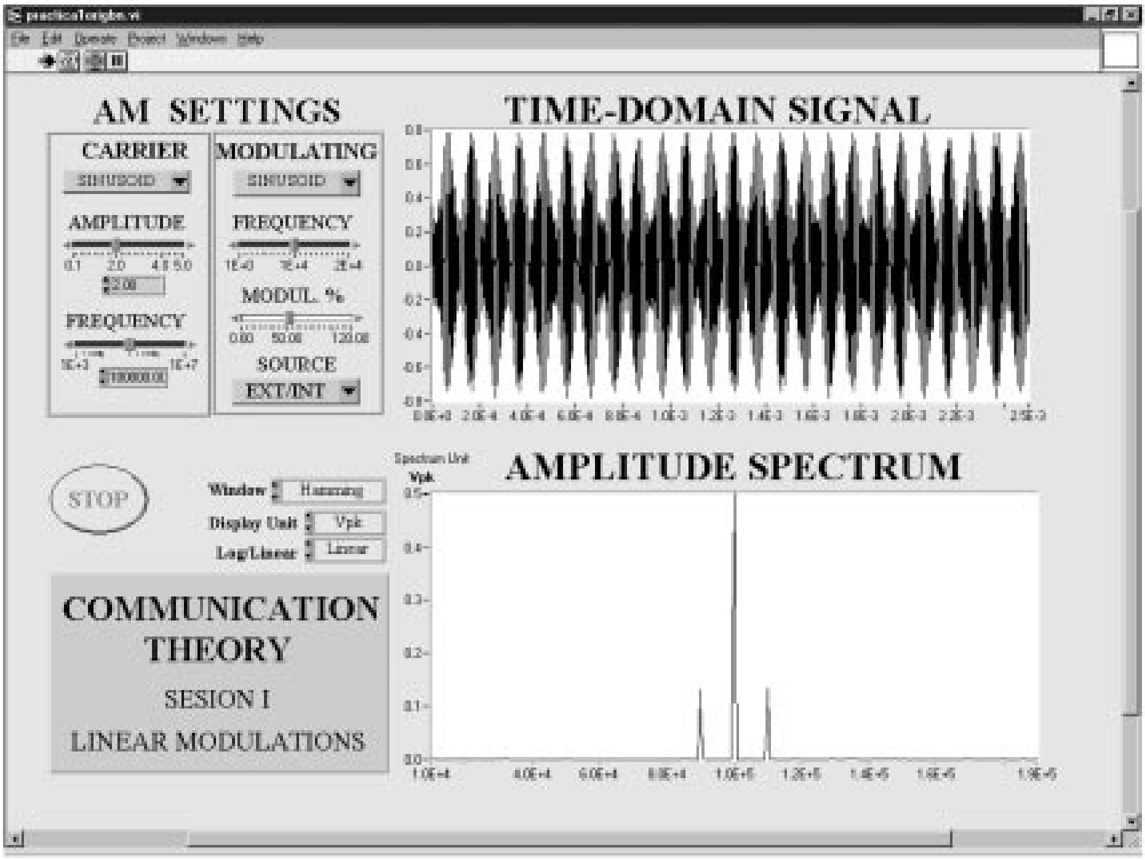

Fig. 2. Front panel of program for AM modulation experiments.

different modulating waveforms are employed (square and triangular periodic waves, noise, etc.). The sound perceived can be related by the student to the harmonic contents of the demodulated wave.

Finally, the audio signal coming from a microphone is introduced at the rear input of the signal generator, thus modulating the carrier signal. A simple op amp inverter is employed for amplifying the microphone output so that the required signal levels at the rear signal generator input are obtained. The students visualise for the first time a voice-modulated signal and its corresponding time-varying amplitude spectrum. The effect of varying modulation parameters (e.g. modulation index) in the perception of their own voice strongly motivates them. Also, when they discover that the modulating wave is the microphone signal inverted in polarity (due to the inverting amplifier employed) they become convinced of the subsidiary effect of phase on sound perception.

ANGULAR MODULATIONS

The second set of lab experiments tries to illustrate the concept of angular modulation and to emphasise relevant practical aspects of these modulations. It closely parallels the structure of the linear modulation experiments, so that the student goes through a familiar set of procedures. The most important type of angular modulation, i.e., frequency modulation (FM) is studied. The student generates different FM modulated waves, and analyses the effect of various modulation parameters, both in time and frequency. Then he or she builds an FM transmitter able to transmit in the commercial broadcasting range of 88 to 108 MHz, so that the transmitted signal can be detected by a simple FM radio receiver. Important effects such as the threshold effect and the capture effect [7] are illustrated.

Figure 3 shows the main window of the program running on the PC for this second set of experiments. Its operation is very similar to that of the program in Fig. 2 described in the former section. It is actually an adaptation of the former program to work with angular modulations. Both time and frequency representations of the acquired signal are obtained.

First, FM tone modulation is analysed. A 0.2-Hz sinusoid is employed for modulating a carrier of 100 kHz with a maximum frequency deviation of $\Delta f = 50$ kHz. Such parameters are well suited for good visualisation by the oscilloscope of the frequency modulation process. The student can see how the modulated wave is a sinusoid varying in frequency from 50 to 150 kHz sinusoidally every 5 s. Then, the influence of the modulating wave on the carrier is identified, and the concept of maximum frequency deviation readily noticed. As a byproduct, a deeper insight into the oscilloscope trigger is gained when the student interprets the modulated signal in the oscilloscope screen that looks like an oscillating 'spring' with a fixed terminal. The student can observe that, contrary to AM, an FM wave is best viewed by using as a trigger source the carrier and not the modulating wave. Concerning the amplitude spectrum observed, a single sharp lobe moving sinusoidally from 50 to 150 kHz every 5 s is noticed by the student, who readily relates it to the behaviour observed in the time domain but not with the theoretical FM spectrum for tone modulation [7]. Once more, the fact that the truncated waveform is being acquired explains this fact, showing again to the student the practical limitations in the measurement of real signals.

Next, different modulating waves are employed (square, triangular, noise, etc.) allowing to identify their effect in the way the carrier frequency is varied. In particular, the student observes that a triangular modulating wave leads to a linear frequency sweep, that a square wave produces step frequency transitions (the analogue with FSK is then noted) and that noise produces an erratic frequency variation.

Some practical aspects such as the measurement of the FM bandwidth and the characterisation of FM modulators are analysed afterwards. To achieve this goal, an FM tone modulation is employed, now with a larger modulating frequency (10 kHz). This allows that in the acquisition window many cycles of the modulating wave will be present, leading to a fair spectral representation. The student estimates the bandwidth, both in narrowband and wideband FM conditions [7], by counting the spectral components larger than 1% of the unmodulated carrier component, and compares it with the empirical Carson's Rule [7]. Then the student varies the amplitude of the modulating tone from zero to the value that eliminates the carrier component in the spectrum for the first time. At this point the modulation index is 2.4, so that the student can determine the frequency sensitivity of the FM modulator built in the signal generator.

Finally, students build an FM transmitter by inserting a wire to the signal analyser output that acts as an antenna. Since the maximum carrier frequency of the signal generator is 15 MHz and the frequency range that FM radios can detect corresponds to 88–108 MHz, the student employs a periodic square wave as carrier [6]. He or she observes in the amplitude spectrum graph how the n-th harmonic of the square wave acts itself as the carrier of a residual FM modulation of the same modulating signal but with a maximum frequency deviation n times larger. Then the student determines how to choose the square wave frequency so that one of its harmonics falls into the

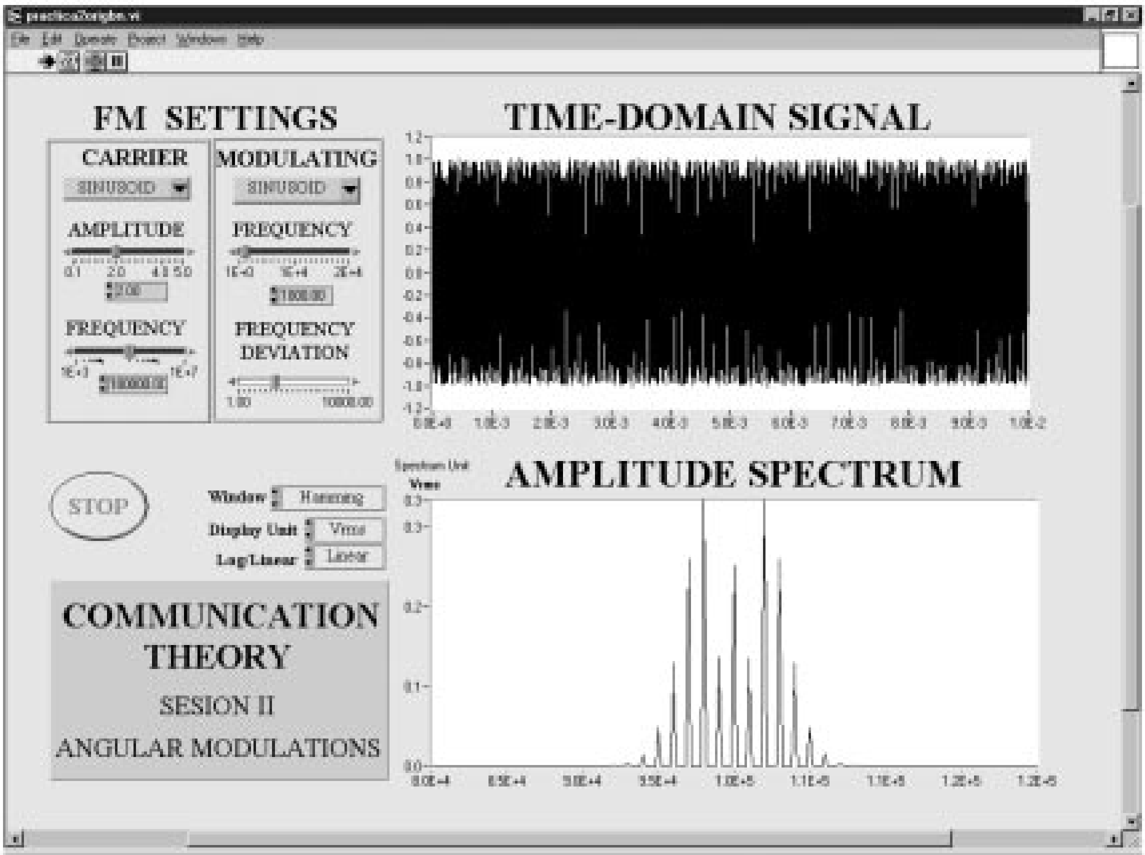

Fig. 3. Front panel of program for FM modulation experiments.

88–108 MHz range, and tune its walkman to it. Similarly to the AM case, the tone and intensity of the received sound are related to the parameters of the modulating wave. The student can assess the cleaner sound obtained using FM as compared to AM, and the sudden degradation observed when he or she is separated from the antenna a certain distance (threshold effect). The effect of the de-emphasis filter [7] can also be assessed. The capture effect can be illustrated by using the same carrier as a commercial FM station and increasing the carrier amplitude so that our interfering transmission completely mutilates at a certain carrier level the commercial transmission. The interference changes abruptly from being negligible to completely dominating the received sound.

RANDOM SIGNALS AND NOISE

The third set of lab experiments tries to show the student the main tools and parameters required to characterise random signals and noise, and the effect of filtering on such signals. To achieve this task, the same environment is employed (but the walkman is no longer required), and a different program, shown in Fig. 4, is used. Such a program uploads the signal acquired by the oscilloscope and performs a complete set of measurements in order to characterise it statistically, assuming that the signal acquired comes from an ergodic random process [7]. First, it calculates important average parameters such as mean, variance, standard deviation, etc. At the same time, the probability density function (PDF) is estimated by calculating the averaged amplitude histogram over a certain number of acquisitions and then scaling it. Such a set of measurements allows students to characterise the expected value of the signal at a certain instant, but provide only a partial characterisation of the signal, since the interdependence of the successive sample values is not estimated. To do so both in time and frequency domains, a second set of measurements is performed. First, the periodograms [7] (square of spectrum amplitude scaled) of the successive acquisitions are averaged, leading to an estimation of the power spectral density (PSD) unction [7]. By applying the inverse FFT, the autocorrelation function [7] is obtained.

Using this program, the student characterises the noise generated by the signal generator and estimates its Gaussian nature, the flatness of its PSD and its power and DC values. By observing the program windows, the student identifies the relationship between the PSD and autocorrelation function, as well as several ways to obtain the signal power: calculating variance and mean values, measuring the autocorrelation function at the origin or estimating the area under the PSD. By varying different noise parameters in the signal

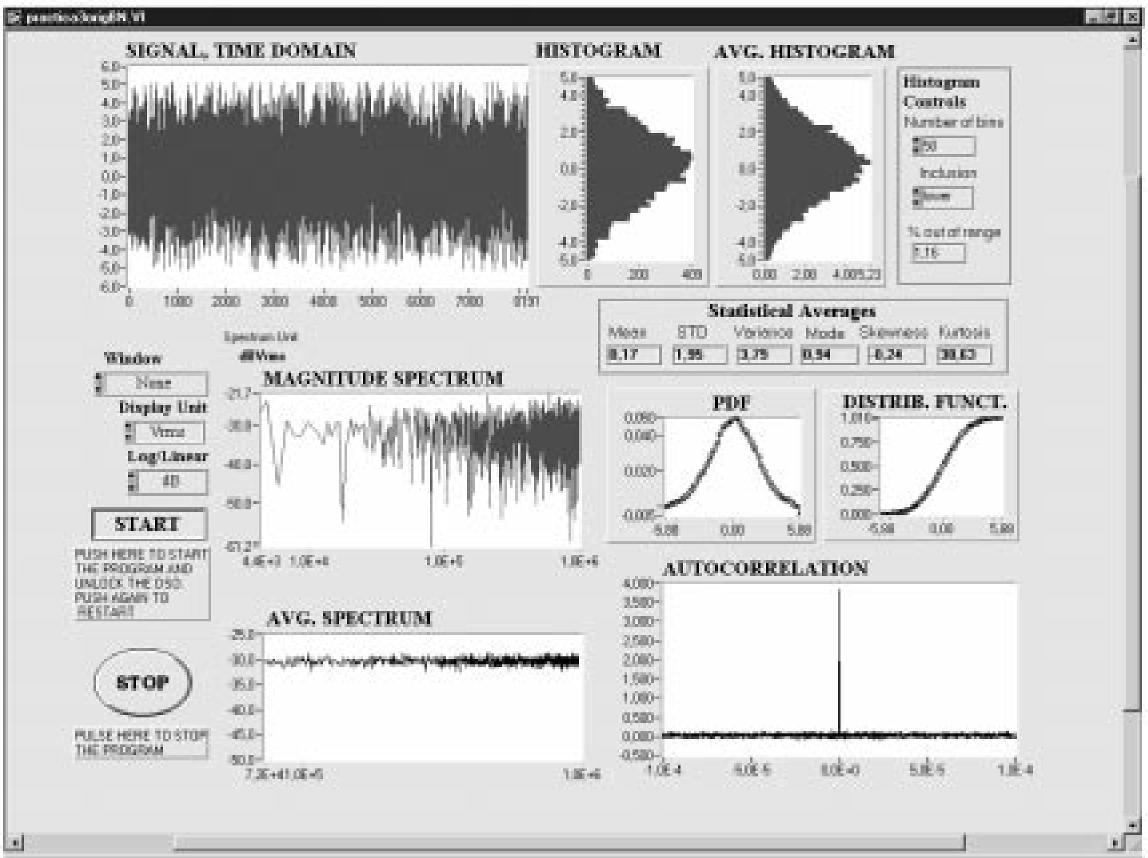

Fig. 4. Front panel of program for random signals and noise experiments.

generator (RMS value, offset) the effect on the different measured parameters and functions can be evaluated.

Then, the student builds a simple RC low-pass filter and applies the signal generator noise at its input, now characterising the output noise. He or she can observe how filtering reduces power and increases correlation, and can measure decorrelation time and see how the output PSD is a good estimate of the (squared) filter magnitude response if the input noise has uniform PSD. The equivalent noise bandwidth of the filter can be readily estimated and compared to the theoretical expectation.

The final experiment is designed to characterise periodic signals whose randomness is in their initial phase. For doing so, such periodic signals are generated by the signal generator and acquired by the oscilloscope with the trigger disabled (so that the initial phase can be considered random). First, sinusoidal waves are analysed. Once more the truncation inherent to the acquisition of a periodic wave leads to differences in the autocorrelation function and PSD that can be identified by the student. Then, square waves are employed and the dependence of the statistical measurements with the duty cycle can be observed. Finally, triangular waves are analysed. The resulting estimated PDF and statistical parameters (mean, variance, etc) are identical to those of a noise with uniform PDF. This helps the student to understand that these measurements are not enough for the statistical characterisation of the signal, and that PSD and autocorrelation are important additional measurements.

IMPACT OF THE LAB EXPERIMENTS AND CONCLUSIONS

The lab experiments described in this paper offer students the possibility to experience the fundamental concepts of analogue modulation and noise simultaneously with their theoretical study and in a hands-on environment. The required lab benches employ inexpensive and widely available equipment. Such experiments have been applied for three years now and the experience of the author is very positive. He has found that students have a deeper grasp on the concepts of noise and modulation, as well as greater motivation and encouragement for acquiring the basic concepts involved, once they experience them in everyday items, such as the walkman. The opportunity to apply the theoretical concepts acquired to real-word signals and systems is highlighted when students are asked about the experiments. The realisation that even simple and rudimentary equipment was all they needed for their first radio broadcasting experience particularly motivates them.

To conclude, a quantitative assessment of the impact of the lab experiments. The exam results in the last three academic years experienced an 11.7% increase on the average with regard to the last academic year without the lab experiments. The author would be glad to provide the lab notes and programs to anyone interested in them.

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