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An intrinsic noise experiment for undergraduate electronic engineering students

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ABSTRACT: Intrinsic noise in electronic systems has a random nature and may be miniscule compared to other signals, such as the desired signal and externally generated noise, yet is predictable given adequate parametric data on the device(s) used. However, it may be very difficult to measure this type of noise using standard laboratory equipment. In this paper, the authors review a stage three undergraduate electronics laboratory experiment (lab) exploring intrinsic noise using a simple circuit comprising two operational amplifiers (opamps), a zener diode as noise generator and standard laboratory equipment. The rationale and development of the lab is discussed, followed by its validation using actual data. It concludes that an intrinsic noise lab has been conducted successfully without the use of high-technology equipment or materials, within the confines of a usual teaching electronics laboratory. Some recommendations and comments are also made.

INTRODUCTION

The Christchurch Polytechnic Institute of Technology (CPIT) in Christchurch, New Zealand, offers a three year Bachelor of Engineering Technology in Electrotechnology. The curriculum for final year students in the electronics elective includes a fair exploration into design techniques that minimise noise in systems. Noise can be either *extrinsic* (external) which means it is derived from sources outside the system, or *intrinsic* (internal), derived from the circuit itself. Extrinsic noise is mainly *human-made*, thus it may vary to a large degree and may constitute a level that masks signals of concern.

However, intrinsic noise is a more quantifiable type of noise, since it is fundamental. It can also be called quantum noise as it is caused by potential fluctuations associated with the movement of discrete charge quanta, most notably electrons. This noise can be accurately predicted based on specified physical properties of the components used to construct the system and may also depend on temperature. Although intrinsic noise is detectable, its magnitude may be some orders smaller (μV or less) than normal signals (mV or more), making it difficult to detect in the presence of a normal signal and also in the presence of extrinsic noise.

Standard equipment in the CPIT laboratory at this level of tuition includes an adjustable dual power supply, a function generator, a multimeter, a digital storage oscilloscope as well as a true root-mean-square (r.m.s.) instrument, which is primarily used for measuring total harmonic distortion. Due to the random nature of intrinsic noise, it is difficult to quantify a noise signal by measurement using a time-domain instrument and, therefore, such measurement would typically require a spectrum analyser. A spectrum analyser is an expensive instrument, especially when designed for radio frequency applications. For the purposes of learning about noise, it is sufficient and practical to limit the frequency spectrum to the audio range, but this range is not particularly well catered for in standard spectrum analysers. Although there are several economical computerised data-logging systems available to perform spectral analysis, this laboratory is not (yet) supplied with a computer per test station.

The authors could not find any laboratories on this topic in peer-reviewed journals, and had to go to the Internet as a last resort. Initially two such *labs* were found. As an example, the first is a demonstration into the use of *PSpice* to simulate and thus predict the intrinsic noise in a MOS-based differential amplifier [1]. It stems from an advanced course in analogue integrated circuit design and is very useful in demonstrating the application of *PSpice* in a virtual environment, but does not show any evidence of actual physical testing.

Further searching has produced some more evidence of labs on intrinsic noise. The majority have been developed in departments of physics at universities, and, as expected, show a rigorous theoretical treatment of the topic [2-4]. All three labs use sophisticated instrumentation of which the *lock-in amplifier* is prevalent. This instrument can successfully extract a single tone (frequency) embedded in noise. The CPIT does not have such an instrument, and cannot justify acquiring one at present.

Of particular interest is the lab where a zener diode is used as primary noise generator, then sums a sinusoidal signal to create a noisy signal [4]. This signal is then *decontaminated* by using a lock-in amplifier. A search on a hobbyist Web site has revealed a collection of noise generators, where the use of a zener diode as noise source is popular [5]. Some designs use a reverse-biased base-emitter junction of a small-signal transistor at the onset of breakdown, at a potential of between 5V and 10V via a high-value resistor such as 100kΩ. Special care needs to be taken to avoid damaging the junction, as Avalanche breakdown occurs very rapidly.

Whether using a zener diode or a reverse biased transistor junction, the maximum noise apparently occurs at the onset of breakdown, and is significantly larger at small current than at a larger current. It is also reported that higher voltage zener diodes also tend to generate more noise than their lower value counterparts [4]. An example is where a zener diode generates $0.1\mu V/Hz^{1/2}$ of noise at a bias current of 0.1mA. This value drops appreciably by an order of magnitude for a current of 10mA, suggesting an inverse root law [6].

Some useful advice is offered on practical measurement of noisy voltage [6]. As stated, *The most accurate way to make a noise measurement is to use a true r.m.s. voltmeter* [6]. An averaging type alternating current voltmeter can also be used, but provides less accuracy due to its inherent low pass nature, and even an oscilloscope can be used if the peaks are multiplied by $^1/_6$ to $^1/_8$.

Finally, a lab *warm-up* from an electrical engineering degree in stage three explores a dual stage opamp circuit that produces a high gain to amplify thermal (Johnson) and amplifier noise [7]. Total output noise is explored using an oscilloscope. Useful advice is offered on the construction of the circuit using a breadboard to minimise external (interference) noise.

It has been reported that laboratory instruction has not, in the last decade or so, received much attention [8]. Since 1993, only about 6.5% of papers appearing in the *Journal of Engineering Education* used *laboratory* as a keyword. Those authors ascribe this to the emphasis on the curriculum and teaching methods in engineering education. A quick review of other peer-reviewed publications in engineering education has shown a rather similar tendency. Finding a specialised *lab* is, therefore, rather unlikely. A custom-made lab has subsequently been designed to demonstrate that it can be achieved successfully using a simple circuit, standard equipment and in a standard laboratory environment. This lab has been trialed by a group of stage three undergraduate students. Results are presented, including measurement data and a student survey.

METHODOLOGY

The overall aim of the lab is to familiarise students with the intrinsic noise in and around a typical integrated opamp circuit. This familiarisation comprises studying manufacturer's data sheets of semiconductors for noise related parametric data, as well as the physical indirect measurement of noise and breaking the combined signal down into its constituents.

The objectives for the lab are as follows:

- To estimate noise related parameters around opamp circuits;
- To perform simple measurement of noise related values for opamp amplifiers, using various techniques;
- To indirectly measure, then derive, noise generated by a zener diode;
- To distinguish between different intrinsic noise sources;
- To gain an appreciation for the difficulty in measuring intrinsic noise in the presence of external noise.

From a pedagogical point of view, the aim and objectives requires the student to exercise, or at least experience and build, a wide range of technical and non-technical skills [9]. This includes the skills of experimentation, *real world*, build (assembly), discovery, equipment, motivation, communication and independent learning. Figure 1 shows the circuit used. The frequency-compensated opamps are contained within the LM324N quad-opamp device.

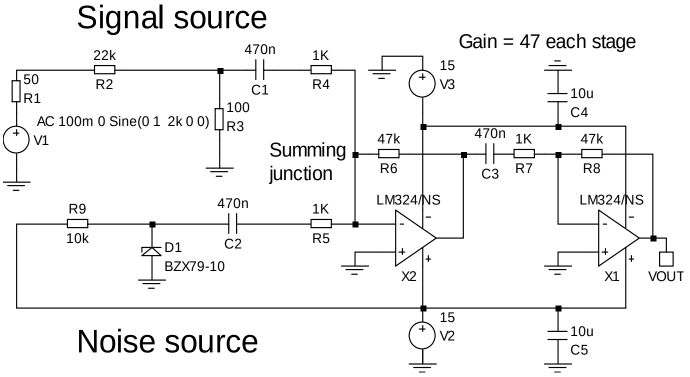

Figure 1: Schematic diagram for the bandwidth limited random noise generating circuit used for the lab.

A simple circuit has been designed so that it could be easily constructed by a student on a solderless prototype board (breadboard), using easily accessible and economic components. A random noise source is summed with a low-noise signal. The sum is then amplified by an inverting opamp circuit by a factor of 47, then amplified by another inverting opamp by another 47 times, to produce a total gain around 2,200 (67dB). The student assembles this circuit on a breadboard taking due care to avoid unnecessary pickup of external noise, for example by avoiding long wires or long component leads and also by using adequate decoupling (C4 & C5). This avoids potential problems like external noise pickup and internal instability (oscillation).

A further technique for reducing external noise pickup is to use simple passive high pass filters as shown. This is implemented by AC-coupling the noise and signal sources and subsequent amplifier stages, using dual frequency breakpoints of around 340Hz. The corrected -3dB point due to multiple poles is 530Hz. This is sensible due to the relaxed roll-off of passive filters and also to practically eliminate the majority of mains 50Hz and its major harmonics. Also important is to twist the power supply leads together. This further reduces 50Hz, or related, pickup, due to minimized loop area, which consequently minimizes magnetic coupling.

A *noiseless* signal source is created by utilising a standard function generator set at an output of around 100mV r.m.s., together with a resistive attenuator, in order to ensure that the signal is sufficiently small, yet reasonably noise free.

The *noise* source comprises a very lightly biased zener diode (BZX85C9V1). To ensure that the zener diode is functioning properly, the student should check its bias voltage, which should be close to (just under) the nominal Avalanche breakdown voltage of 9.1V. The AC signal from the zener diode, now representing the noise source, is then coupled into the amplifier circuit via capacitor C2 at the summing junction.

The relatively large gain provides ample opportunity to amplify a (still) relatively small amount of noise. However, the high gain will cause a significant reduction in bandwidth if only one opamp is used; hence two are employed, sharing the gains to increase the bandwidth. The effective bandwidth can be estimated easily by referring to the manufacturer's data sheet for the opamps. With a typical roll-off of

20dB/decade (for frequency compensated opamps such as the LM324) down to a transition frequency f_t of 1MHz, this would produce a high frequency -3dB cut-off point of approximately 22kHz, derived from a 33dB gain for each opamp. Consequently, the corrected actual -3dB point due to multiple poles becomes 14kHz.

Students then proceed to measure the output voltage of the amplifier against time using an oscilloscope and also a true-r.m.s. voltmeter. Separate measurements for the following cases are then recorded, as follows:

- Signal source disconnected, zener diode biased;
- Signal source disconnected, zener diode unbiased (connect *Vcc* lead of R1 to ground, to simulate equivalent impedance);
- Adjust function generator until amplifier output voltage (zener diode still unbiased) is 1V r.m.s; this is quite a challenge since there is a lot of noise present, even without the *noise* source connected. This can be assisted significantly by the use of digital averaging, if available. Now measure output the r.m.s. voltage.

Preparation for the lab requires the student to estimate all sources of intrinsic noise based on data sheet parameters and calculation. The student does not need to characterise the environmental or external noise, since the assumption is that there is no significant external noise except mains power noise, which is effectively filtered out. This has to be verified by checking the oscilloscope for tell-tale signs of 50Hz (60Hz) or its harmonics.

Parametric data on noise for the LM324N, the majority of 741 manufacturers' data sheets, and also for zener diodes, is extremely rare. It is the understanding that this is due to these devices being extremely noisy, and would only be published if the values were relatively low, such as for low noise applications.

The only true preparatory estimation would be to quantify the Johnson noise generated by the resistors, and especially so for the contribution of the first stage. As a guide, when considering total noise factor of cascaded amplifiers, the vast majority of noise comes from the first stage provided there is adequate gain in that stage.

Through careful measurement of the total gain of all output voltages listed above and by using a method of elimination, resistive noise (previously estimated) can be deducted from the total output noise with the *noise* source disconnected (zener diode unbiased as stated above) and a figure can be found for amplifier noise only.

This figure would include both elements of noise current i_n and noise voltage e_n in combination. These parameters represent the equivalent sources of noise at the input of the amplifier. Finally, students must derive signal to noise ratios and, consequently, the noise figure based on the measured values. Students have to discuss the results and reach conclusions.

The total output r.m.s. noise voltage can be broken down into its constituents, as follows (the assumption is that all voltage constituents are random and independent of each other):

$$V_{onTOT} \cong \sqrt{V_{onJ}{}^2 + V_{onZ}{}^2 + V_{onA}{}^2} \qquad (1)$$

where:

V_{onJ} ≡ Johnson r.m.s. noise voltage referred to the output;

V_{onZ} ≡ Zener diode r.m.s. noise voltage referred to the output;

V_{onA} ≡ Amplifier r.m.s. noise voltage referred to the output.

Output noise, as a result of the resistors (Johnson noise), is dominated by those in the first stage. This can be estimated as follows:

$$V_{onJ} \approx \sqrt{kTB}\sqrt{\{(R_3 + R_4)//(R_5 + R_9)\}A_v{}^4 + R_6 A_v{}^2} \qquad (2)$$

where:

$k \equiv 1.38 \times 10^{-38}$ J/K;	*Boltzmann's constant*
$T \equiv 290$ K;	*Temperature*
$B \equiv 1.22 \times 22 \times 10^3$ Hz;	*Bandwidth, corrected for 2nd order roll-off*
$A_v \equiv 47$	*Voltage gain of each stage*
$A // B \equiv (A^{-1} + B^{-1})^{-1}$	*So-called* parallel operator

This should yield a value of V_{onJ} ≈ 23pV, which can be ignored.

The addition of a signal source to the noise is treated as the root sum of squares, as it is uncorrelated with noise, as in (1) above.

Students are also expected to estimate the signal to noise ratio (SNR), the noise factor (F) and the noise figure (NF), as follows:

$$SNR = \left(\frac{V_s}{V_n}\right)^2 \qquad (3)$$

where V_s and V_n are the signal and noise voltages, measured at the same point, respectively (normally expressed as r.m.s. voltages). The expression for noise factor is:

$$F = \frac{SNR_i}{SNR_o} \qquad (4)$$

where the subscripts *i* and *o* refer to the input and output, respectively. Finally, the expression for noise figure is:

$$NF = 10 \log F \qquad (5)$$

Students then have to attempt to find some relationship between zener diode biasing current and zener diode noise.

RESULTS

The results include a set of measurement data produced by a sample student and an author, plus a short survey directly after completion of the lab. The measurement data show actual measurements for comparison, while the survey results show student response.

Measurement data are given in Table 1. Figure 2 shows zener diode characteristic noise plots as a function of reverse bias current, Figure 3 shows a photograph of the actual circuit, and Figure 4 shows a *screenshot* of the output noise voltage. The image in this figure was captured using Zener1 with a 10kΩ bias resistor at 0.6mA and produced 1.2Vrms at the output representing a zener noise signal of 580μV r.m.s. from a measured total gain of 2,070.

Table 1: Measurement data (* denotes data from Zener1 and Zener2, respectively – refer to Figure 2).

	Measurements by the Authors	Measurements from a Student	Unit of Measure
Amp noise (output of amp)	12	12.8	mV (rms)
Noise source output (referred to input of amp)	580 / 43 *	79	µV (rms)
Signal source output (referred to input of amp)	420	440	µV (rms)
Input SNR	-2.81 / 19.88 *	29.85	dB
Output SNR	-2.81 / 19.79 *	29.83	dB
Noise figure(NF)	- / 0.09 *	0.02	dB
Amp upper -3dB frequency	15	9.0	kHz
Amp lower -3dB frequency	490	450	Hz
Noise source output (I_z=1mA)	approx. 230 / 80 *	22	µV (rms)
Noise source output (I_z=0.6mA)	580 / 43 *	79	µV (rms)
Noise source output (I_z=0.4mA)	approx. 420/ 330*	154	µV (rms)

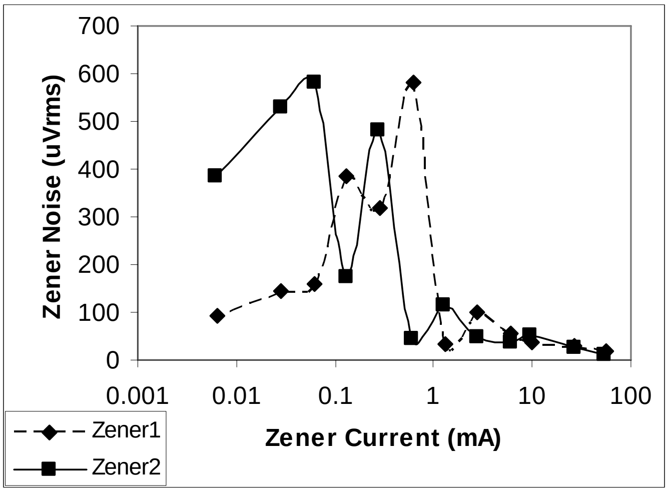

Figure 2: Graph showing characteristic noise plots of two similar zener diodes – note the large difference.

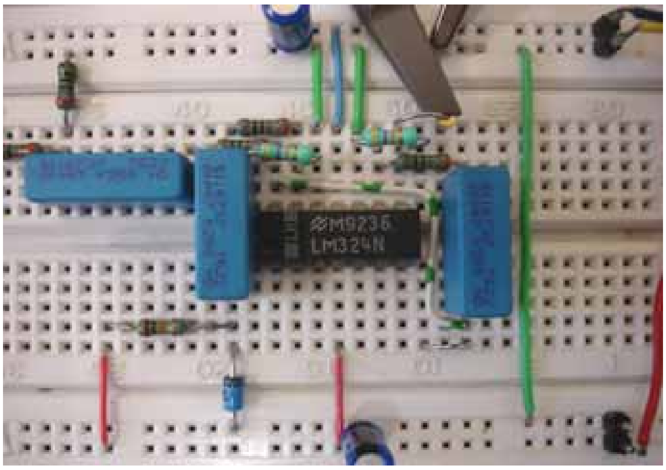

Figure 3: Photograph of the practical circuit.

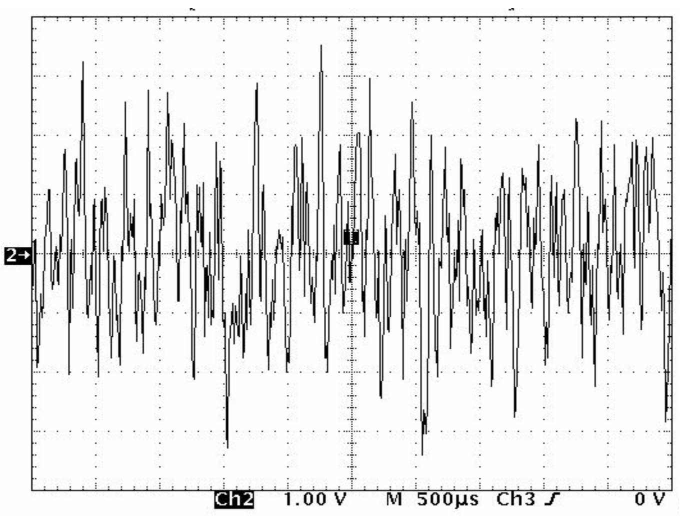

Figure 4: Oscillograph of the output voltage with the noise source connected and the signal source disconnected.

Survey Structure and Results

A survey had been conducted to gauge satisfaction. This is an *often-used measure of success* of a lab [8]. The survey covers three broad areas and relate to the basics, the learning environment and the overall opinion. In the basics section, students were invited to rate three aspects in terms of whether they were too long/difficult/complex, about right or too short/ easy/primitive. The aspects cover the length of the lab, level of difficulty, and usability/relevance of lab equipment. In the learning environment section, students were invited to confirm or deny helpfulness and comment on the following three aspects, notably assist learning and understanding of the theory; learn more skills or gained more knowledge; and personal assistance and guidance offered by supervisor. The last section simply invited comment to gain an overall opinion.

A total of seven students were surveyed using an anonymous questionnaire. This represents the entire population (100% sample). The data was collected and collated by a third party.

In the basics section, six out of seven responses rated *about right* across the three aspects. This represents an 85% level of satisfaction.

In the learning environment section, six out of seven responses confirmed helpfulness across the three aspects. Again, this represents an 85% level of satisfaction.

In the last section (overall opinion), five out of the seven surveyed provided the following comments:

- *Great lab – if your circuit works!*
- Requested that the lab instructions be given earlier to enable better preparation;
- *Enjoyed lab. Challenge to build circuit. Probably tricky report to write*;
- *Overall very good. A set of (range of likely results) for SNRs and noise factor, figure would give us a good idea whether on right track*;
- This (international) student compared this lab to the expected training in his country, commenting that he had to spend a lot more time and effort on the practical circuit rather than being an *arm-chaired engineering* student.

DISCUSSION

The measurement data in Table 1 show a huge variability between data in the two columns. This is likely to be the symptom of the range of values found in the characteristic noise data for these zener diodes. For example, the output noise voltages for two similar zener diodes at 0.6mA bias current were 580µV (Zener1) and 43µV (Zener2).

The graph in Figure 2 clearly illustrates substantial differences between the two zener diodes tested. Zener1 has a definite peak between 0.1mA and 1mA and tends to *drop away* on either side, whereas Zener2 shows a more expected trend of rising noise as the bias current is reduced. Both devices show some peaks suggesting a *wavy* characteristic and they show a basic tendency of increased noise with decreased bias current.

The variability in noise between these devices suggests a wide spread of values from student to student. Although this may not appear to be satisfactory at first, it shows that these diodes have probably not been designed to produce consistent noise. Instead, they produce a range of values in the laboratory ensuring no identical data between students. This is useful and perhaps appropriate where students have a tendency to *share* data that is not acceptable for this lab, where this situation may otherwise be difficult to counter.

In the survey, the basics and learning environment sections both showed a high satisfaction rate of 85%, which is considered fair. In general, the comments offered in these sections are positive and indicate that students enjoyed the lab, learnt to apply the theory in practice, found the learning environment very supportive and some students developed a better appreciation of difficulties involved in this area of practical electronics.

Although the survey was conducted on a very small population (full sample), the general indication is that the experiment was well received and provided a valuable and supportive learning experience. This is consistent with a substantial majority of responses received. In the last section, some valuable suggestions were made for improving this lab. Comment 5 is not surprising, given that it is generally agreed that simulations should not replace physical labs [8]. This is a classic case of listening to the student.

CONCLUSION, RECOMMENDATIONS AND COMMENTS

The students in the survey reported that they found the experiment to be appropriate and provided a valuable and supportive learning environment.

The measurement data presented suggest that the lab produced a range of values, dependent on the particular individual zener diode used. As expected, the general tendency that a zener diode produces more noise as the bias current is reduced has been demonstrated, although there appears to be some unexplained peaks, and similar individual diodes differ significantly.

A laboratory in the advanced topic of intrinsic noise has been performed successfully using standard low-cost equipment and parts, in a typical unscreened laboratory.

More in-depth studies are needed in order to fully characterise zener diodes and to achieve a better understanding of these devices in terms of noise. Finding a device with more predictable noise characteristics would simplify the lab in terms of expected answers. Devices for consideration would be those that offer a relatively low break-down (Avalanche) voltage, including reverse biased bipolar junctions, and perhaps even junction field effect transistors.

To further augment this lab, a *PSpice* simulation is conducted on a known device, for which explicit noise parameters are available.

A colleague from another institution suggested exploring the use of acoustics to demonstrate noise, including such phenomena like shot noise, burst noise and 1/f noise. A high quality headphone-amplifier system may illustrate these effectively to students, provided that they have normal hearing.

The authors would be pleased to hear from other colleagues about any useful techniques in helping students to obtain a maximal outcome from such a lab, and invite further comment or debate. Please contact the first author at cronjet@cpit.ac.nz.

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8th Baltic Region Seminar on Engineering Education: Seminar Proceedings

edited by Zenon J. Pudlowski, Norbert Grünwald & Romanas V. Krivickas

These Proceedings consist of papers presented at the *8th Baltic Region Seminar on Engineering Education*, held at Kaunas University of Technology (KUT), Kaunas, Lithuania, between 2 and 4 September 2004. Eight countries are represented in the 29 papers, which include two informative Opening Addresses and assorted Lead Papers. The presented papers incorporated a diverse scope of important and current issues that currently impact on engineering and technology education at the national, regional and international levels. The level of Lithuanian participation indicates the nation's commitment to advancing engineering education in the higher education sector.

In this era of globalisation, much needs to be done and achieved through creating linkages and establishing collaborative ventures, especially in such a highly developed area as the Baltic Sea Region, and the KUT definitely leads the way in these endeavours. Hence, the aim of this Seminar was to continue dialogue about common problems and challenges in engineering education that relate to the Baltic Region. Strong emphasis must be placed on the establishment of collaborative ventures and the strengthening of existing ones.

It should be noted that the Baltic Seminar series of seminars endeavours to bring together educators, primarily from the Baltic Region, to continue and expand on debates about common problems and key challenges in engineering and technology education; to promote discussion on the need for innovation in engineering and technology education; and to foster the links, collaboration and friendships already established within the region.

The papers included in these Proceedings reflect on the international debate regarding the processes and structure of current engineering education, and are grouped under the following broad topics:

- Opening addresses
- New trends and approaches to engineering education
- Quality issues and improvements in engineering education
- Specific engineering education programmes
- Innovation and alternatives in engineering education
- Important issues and challenges in engineering education
- Case studies

All of the papers presented in this volume were subject to a formal peer review process, as is the case with all UICEE publications. It is envisaged that these Proceedings will contribute to the international debate in engineering education and will become a source of information and reference on research and development in engineering education.

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