"Where did we go wrong?"

An examination of students treatment of experimental error in engineering mechanics laboratories

Tim Anderson
Department of Engineering, University of Waikato, Hamilton, New Zealand
tna2@students.waikato.ac.nz

Rob Torrens
Department of Engineering, University of Waikato, Hamilton, New Zealand
torrens@waikato.ac.nz

Mark Lay
Department of Engineering, University of Waikato, Hamilton, New Zealand
mclay@waikato.ac.nz

Mike Duke
Department of Engineering, University of Waikato, Hamilton, New Zealand
dukemd@waikato.ac.nz

Abstract*: The ability of engineers and applied scientists to undertake experimental measurements is a fundamental requirement of the profession. However, it is not simply good enough to be able to perform experiments if we are not able to interpret the results. In this study, reports prepared by mechanical engineering students were examined to determine how students dealt with the disparity between experimental measurements and theoretical results in their Engineering Mechanics laboratories. Analysis of the reports, and discussions with students in their laboratory classes, revealed a superficial understanding or regard for experimental error. This superficial treatment of experimental error is, most likely, due to a number of factors that are discussed. Some possible strategies for addressing the issue are also examined.*

Introduction

From a historical perspective, engineering draws it origins from the artisans. Traditionally, technology developed incrementally by refinement of ideas and skills passed from artisans to apprentices.

The "modern" concept of university based engineering education started in France in the late 18th century with the establishment of the Ecole Polytechnique. This saw students undertaking entrance examinations and being given a mathematical backing before moving into a specific field of engineering (Ferguson, 1992). Building on the French system of mathematical rigor, the development of engineering schools in the USA in the mid 19th century saw a high emphasis placed not only on lecture based instruction but also hands on experience in laboratories (Feisel and Rosa, 2005)

One of the modern challenges to "hands on" learning has been the development of cheap computing technology and high level simulation software. There is a temptation to reduce the use of hands on instruction in favour of computer based simulation. The short-coming of this approach is that students may miss out in understanding the inadequacies of a theory's ability to explain phenomena that can only be observed through hands on experience (Magin and Kanapathipillai, 2000).

Benjamin Franklin said "In this world nothing can be said to be certain, except death and taxes" (Knowles, 2005) In almost all our undertakings in the physical world we are faced with a degree of uncertainty, irrespective of humanity's implicit assumption that it can strictly control its environment.

The failure of this assumption is most clearly illustrated when undertaking any experimental work. If we resort solely to the use of simulation we can act to "hide" experimental error and could potentially present a trivial outcome.

Therefore, to demonstrate engineering in the "real" world it is important that engineering students undertake practical exercises. During this time students will come face to face with the reality that experimental data does not necessarily correspond to the ideal theory. This was indeed the case in Hudgins and Reilly's (1989) study of student chemical engineers understanding of experimental error. In this frank discussion, Hudgins and Reilly infer that there is an innate desire from students for experimental data to lie perfectly on clean line. The irony of this desire however lies in the fact that the "clean line" students in the study were hoping to achieve was actually empirically derived from a large data pool. Furthermore, they note that when confronted with scattered data, that the students did not understand experimental error, and that this had led to the perception of the experiment being "wrong" or a "bad experiment".

Tomlinson *et al*. (2001) found that the first year chemistry students in their study had a poor understanding of key terms relating to experimental errors. In this study they highlight an interesting misconception of students that "errors" result from personal mistakes rather than being "normal" variations. This supports Hudgins and Reilly's premise that students have difficulty confronting scattered experimental data. Furthermore, Tomlinson *et al*. 2001 suggest that student understanding of errors and the language relating to them could be improved, by challenging students to provide evidence of random errors in their data, as well as precautions taken to avoid systematic errors.

Despite the numerous advances made in the field of science and engineering, especially since the industrial revolution, a significant amount of research is still based on obtaining empirical data. However, from the studies discussed it would appear that in some respects, that there has been difficulty in conveying knowledge about experimental error to student engineers. As undergraduate degree programs in engineering were only recently established at The University of Waikato (first offered in 2000 and mechanical engineering c. 2002) it is still in a somewhat developmental stage. As such, it was decided to examine how mechanical engineering students dealt with experimental error in their engineering mechanics laboratories. The aim of this study being to identify and address any shortcomings with regard to students' treatment of the experimental method particularly experimental error.

Laboratory Experiments

The laboratory work examined in this study is part of the subject "Dynamics and Mechanisms" taught to third year mechanical engineering students. The subject examines the application of kinetics and kinematics to mechanical systems and provides an introduction to 3-D dynamics.

In the laboratories students undertake up to 12 laboratory sessions consisting of 38 very simple to relatively challenging experiments. The experiments cover a range of concepts such as force diagrams, pulleys, belts and chain drives, flywheels and mechanisms, so that students become familiar with the practical applications of the theory taught in the subject. The laboratory apparatus and teaching media are those provided as part of TQ Education and Trainings "Theory of Machines" and "Statics" packages.

Upon examining laboratory reports prepared by the students as part of their assessment, some common misconceptions and mistakes were observed. These included precision, significant figures, curve fitting and graphing, and random and systematic errors.

Precision and significant figures

As scientists and engineers it is common for us to hear about the importance of significant figures. However, while examining the laboratory reports it emerged that students did not understand the "significance" of significant figures, often reporting results to a greater precision than what could possibly be measured.

To illustrate this point, take the hypothetical example of a ball being dropped to determine the time it takes to fall 0.5m. From our knowledge of dynamics we know that the distance (s) is a function of acceleration (a), the initial velocity (u) and the time (t) as shown in Eqn 1.

$$s = ut + \frac{1}{2}at^2 \tag{1}$$

Assuming the ball has an initial velocity of 0 m/s, is acted upon by gravity providing an acceleration of 9.8 m/s^2 and falls a distance of 0.5 m. Therefore the time taken to fall this distance can be determined by substituting the values into Eqn. 2.

$$t = \sqrt{\frac{2s}{a}} \tag{2}$$

If we use a calculator or spreadsheet to perform this calculation we may get a result whereby it takes 0.31943 s to fall this distance. However, if we attempt to physically measure the time taken for the ball to fall the 0.5 m with a handheld stopwatch, we find that this only reports time in 0.1 s (or 0.01 s) increments. Therefore, to report a solution to the example such as that given implies that we can measure far more precisely than we actually can. Although this is a somewhat exaggerated example, it is illustrative of one of the common errors presented by students in the laboratory reports. By reporting a *precise* solution to the problem students are not considering if this solution is *accurate*. Of the results presented by students in their laboratory reports in 80% of observed cases, the treatment of significant figures was poor.

Curve fitting and graphing

Another common mistake observed in student laboratory reports was a poor understanding of how to present data in a graphical form, and curve fitting to plot data. Students frequently plotted graphs with the y axis over a narrow range rather than starting from zero. If we quickly glance at a student's graph of machine efficiency at varying loads (Figure 1), it would appear that there is some significance to the variation in the data. However, when we examine the scale of the primary y-axis we see that there is not a large absolute variation in the data. In fact if we re-graph the data on the secondary axis, we find that we have essentially a straight line.

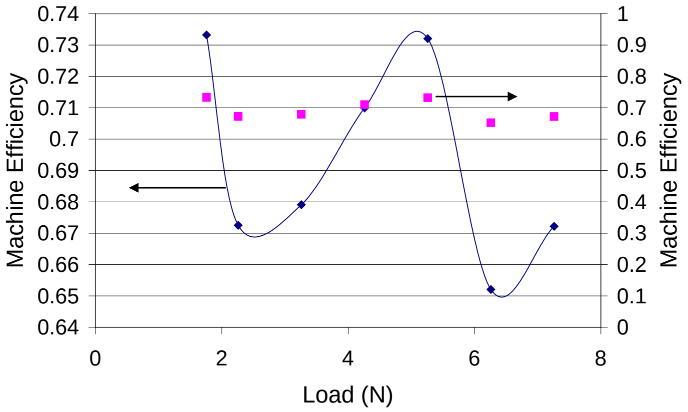

Figure 1: Machine efficiency versus load

Although strictly speaking the graphing of the data is not wrong per se, it is misleading as it suggests that there is some significance to the values plotted rather than merely exhibiting *random error*.

Also observed in student reports was poor curve fitting and understanding of what the presented curve fits implied. Students tended to fit linear equations to non-linear data. Take for example the graph of the mechanical advantage versus the load on a screw jack (Figure 2) that was presented in one of the examined laboratory reports. Here the student has fitted a linear curve to the data and presented the equation of the curve from a linear regression. When examining the plot we find that at a load of 0 N that the mechanical advantage will be 3.5. Obviously this is unrealistic, however the student offered no explanation or discussion on why they used a linear curve fit that did not pass through (0,0). This was a common theme observed throughout the reports and suggests a lack of connection between graphing data, fitting a curve and an understanding of what this represents in a physical sense.

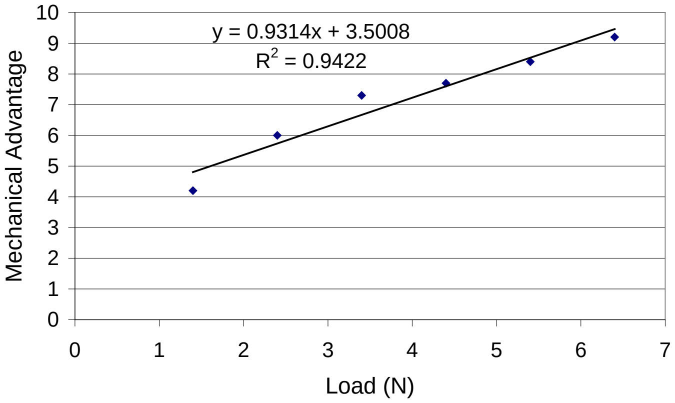

Figure 2: Mechanical advantage versus load for a screw jack

In general, students graphing skills were better than their use of significant figures, however, nearly 60% of the observed graphs presented by students illustrated poor consideration or understanding of graphical presentation.

Random and systematic errors

In some reports the issue of *random error* received superficial treatment at best, or more commonly no treatment at all. More disturbingly, *systematic error* received no mention in any of the examined reports.

One example of error identification was presented by a student measuring gravity using a pendulum. In this experiment a small mass is suspended from a length of string and set swinging from a known height. The time taken for the pendulum to complete 20 oscillations is recorded. Knowing the time taken for an individual oscillation (t) and the length of the string (L) it is possible to calculate a value for gravity (g) using Eqn. 3.

$$g = \frac{4\pi^2 L}{t^2} \qquad (3)$$

From their data, they determined that the value of gravity was approximately 10.2 m/s^2, however they identified that both timing and accuracy in measuring the pendulum length would contribute to error in the experiment although neither *systematic* or *random* error were mentioned by name. This however was the exception rather than the rule for student reports, where on the most part error was generally ignored, or a fleeting reference to “friction in the system” was made. Of the examined reports, over 90% treated errors in a trivial manner, or made no mention of experimental errors.

Discussion and conclusions

From an examination of the student laboratory reports it was apparent that, in general, students were either putting very little thought into their reporting of experiments or were unable to recognize the physical implications of their analysis. The lack of attention to or recognition of experimental errors and their significance presented a somewhat disturbing result. When mentioned it was found that experimental error was addressed, the students’ analysis was found to be generally superficial and may as well have been neglected. Two examples clearly illustrate the lack of understanding of students: “this is a good result due to the inaccuracies in the performance of the experiment” and “this is due to errors obtain (sic) during the experiment”. The reason for lack of discussion regarding experimental error could be due to lack of experience, or the limited time the student spent thinking about the implications of their results. Furthermore, on examination of the course material, it was noted that experimental error was not mentioned in any of the documentation. The absence of this may have led students to the conclusion that it is not important and that therefore they do not need to address it. This corresponds well with what has been discussed previously in the literature and suggests more than an isolated example.

We would expect students to have a sufficient understanding of mathematics to perform a reasonable level of analysis. Prerequisites for engineering are year 13 (seventh form) calculus or statistics in secondary school (highest level before entering university). Also all students complete first year university calculus and algebra, and second and third year engineering mathematics before starting the Dynamics and Mechanisms paper. However, a common complaint from engineering students is that the maths they are taught is abstract and not related to engineering problems. Also the last time students would have formally encountered curve fitting is in year 11 (fifth form). The problem appears to lie with the limited amount of time, care and thought students dedicate to their lab reports, due to the low grade weighting given to the reports and high number of assignments and lab reports expected from the students. Also, it appears good rigor is not enforced by the markers or encouraged by lab demonstrators, usually masters or PhD students who have limited motivation and/or teaching experience. In addition, links between experiments and taught theory may not be readily apparent due to difficulties matching the time students encounter laboratory content with relevant lecture material.

It was also observed that some of the experiments undertaken by the students may be too simplistic and do not encourage a sufficient degree of critical thinking or examination. Additionally the detail provided by the laboratory manual may in fact be trivializing the experiments to the point where students are merely “painting by numbers” and may therefore warrant restructuring.

Moreover, the problems associated with *precision*, *accuracy* and the graphical presentation of results are most likely to be more widespread than just laboratories in “Dynamics and Mechanisms”. It could therefore be suggested that this material be covered in all subjects involving laboratory work. Furthermore, it suggests a need for staff to reinforce these fundamental skills through all aspects of the degree program. In particular the use of significant figures, spreadsheets for graphing and linear regression need to be addressed. In addition, the fact that engineering statistics is not taught until the final year of the degree may be contributing to a general lack of understanding in the field of experimental work and is a potential area for revision.

Finally, the development of a “hands on” subject similar to that discussed by Magin and Kanapathipillai (2000) could present an interesting addition to the degree. The inclusion of such a subject could potentially aid students understanding of the experimental method and the role of errors and may be worthwhile exploring. As experimentation is highly experiential, by exposing students to more of it, it may be possible to improve their understanding.

References

Feisel, L.D. & Rosa, A.J., (2005), The role of the laboratory in undergraduate engineering education, *Journal of Engineering Education*, 94 (1), 121-130

Ferguson, E.S., (1992), *Engineering and the mind’s eye*, Cambridge, The MIT Press

Hudgins, R. R. & Reilly, P. M., (1989), Do Student Chemical Engineers Understand Experimental Error?, *Chemical Engineering Education*, 23 (2), 92-94,119

Knowles, E. (Ed.), (2005) *The Oxford Dictionary of Quotations*, Oxford University Press, Oxford

Magin, D. & Kanapathipillai, S., (2000), Engineering students understanding of the role of experimentation, *European Journal of Engineering Education*, 25 (4), 351-358

Tomlinson, J., Dyson, P.J., & Garratt, J., (2001), Student misconceptions of the language of error, *University Chemistry Education*, 5, 1-8