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Edited by J. C. Gibbings
Excerpt
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The place of the experiment in engineering

It is the nature of man that he is of an inquiring disposition: the new parent faced with the continual plea of 'Why?' soon learns this. We reveal the features of our material world by observation and we do this most effectively when in an organised way. Experiment embodies organised observation and so it is seen in its position of primacy in man's activity. The principles of organising observation were set forth in detail in the early seventeenth century by Francis Bacon, and his basic ideas have stood the test of time (Ref. [1]). Recently Medawar has written: 'Bacon's writing fired and inspired his readers, and can do the same today. He is still science's greatest spokesman' (Ref. [2]). Sometimes, as in botany, we can make observations and logically deduce classifications without resorting to numerical values: but this is rare. As Kelvin is reported to have said: 'When you can measure what you are speaking about, and express it in numbers, you know something about it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science' (Ref. [3]). Measurement then is the prime means of experimental observation.

The totality of experiment is more than just ordered observation for it must include logical deduction from what is observed. An experiment must lead to a conclusion even if that conclusion is that the effect sought does not exist; this can still be of value, as in the famous Michelson–Morley experiment that could not detect that our world was moving relative to the light in the space surrounding it.

Our scientific laws are founded on observation: they are formulated to express what we have measured. As Saint-Exupery made one of his characters say: 'Experience will guide us to the rules', he said 'You cannot make rules precede practical experience' (Ref. [4]). Sometimes the evidence is indirect, almost circumstantial. Think, for example, of the intellectual power of Newton in postulating that the gravitational attraction that man had observed to hold us all upon the surface of the earth also acted through the vastness of space (Ref. [5]), so that he thereby explained the orbits of the planets that Kepler had so laboriously computed (Ref. [6]).

Mostly, analysis and experiment go hand-in-hand, as they must do. This is simply because analysis is an ordered description of a real event and determination of the latter is experimentation. Calculation is always preceded by the construction of an analytical model and it is this model that can be tested only by experiment.

Even though scientific laws and analytical models are based on observed values they continually have to be tested by further experiment. For example, a law may be valid only for either the particular conditions or the limited range and scope of the experiment forming its basis. Osborne Reynolds was scornfully critical in this respect when he wrote 'a certain pride in mathematics has prevented those engaged in these investigations from availing themselves of methods which might reflect on the infallibility of reason' (Ref. [7]). When applying laws and analytical models based on experiment to the process of design, the engineer must be particularly careful to ensure that he is fully aware of the limitations of the original experiment and so must have studied it to the necessary extent.

Southwell, a pioneer in the application of calculation by numerical analysis to engineering problems, stressed the importance of understanding experiments from which data is obtained, when he wrote that 'computational methods should allow for the margin of uncertainty which is there in practice whether we like it or not' (Ref. [8]). A calculation is only as accurate as the experimental data fed into it.

This dependence of analysis upon experimental data can be quite critical. It has been found to be particularly so in design studies that seek an optimised solution. An extreme example now stresses this: an attempt to optimise a fleet of oil tankers gave the first computer output as a fleet of three tankers, each 1 mile in length and travelling at 0.5 knots. Refining the data then gave a second output of 1000 tankers, each 2 in long and travelling at 40 knots. The experimental data was being extrapolated too far beyond the existing range of that data. These matters are highly important to the engineer and it is unfortunate that much teaching of analysis is given as an abstract exercise not related to real events and so the young engineer can readily overlook the importance of assessing the realism of an analytical model. It is not a new difficulty; and even the greatest can fail: a translation of the obituary of a great eighteenth-century mathematician reads: 'So scientists have reproached him for having sometimes lavished his calculus on physical hypotheses, or even on metaphysical principles, of which he had not sufficiently examined the likelihood and solidity' (Ref. [9]). The undergraduate course can give the student a false impression that most of engineering practice is straightforward calculation with reliable data.

Only rarely does a teacher describe problems that cannot, or should not, be solved by analysis. Sometimes an analysis is either too complex to be solved by even the largest computers or, if not so, the running cost of the computer is not justified: sometimes, though the equations are known, the boundary conditions are unknown; and sometimes a phenomenon is so complex as not to be understood and so not describable analytically.

There can be occasions when a calculation can be performed but in the time taken for an extensive analysis, followed by preparation of an extended computer program, the equivalent result can be obtained more rapidly and more cheaply by an experiment. This situation can arise particularly in industry during the development of a design. Making a decision at an early stage on which approach to take is an important part of engineering expertise. In engineering design, engineers continually experiment as part of the development process. Sometimes this experiment can be a statistical study of the failures of a product that occur in service.

Experiment is a highly skilled activity and is never to be thought of as the sole province of the scientist: for the engineer, research and development are closely linked and both rest on the fruits of experiment. Because experiment is intellectually demanding it means that, as Parker has said with reference to industrial laboratories: 'A few people of excellence will probably determine which company wins the world-wide race to be first' (Ref. [10]). This is why training in research is so valuable.

In the way that study must be complemented by practice when learning to play a musical instrument, so also is this true for acquiring a skill in experimentation. Perhaps no more is this true than in the ability to report an experiment. For the undergraduate this book can only be of value when its lessons are tested by a carefully arranged set of laboratory exercises: upon the teacher we would urge the greatest care in the choice and arrangement of such exercises. In teaching there are three purposes for experiment. Firstly, there is the experiment used to illustrate a phenomenon described in a lecture. Secondly, there is the laboratory experiment; either this should give exercise in building an analytical model for the event or it should be the basis for a design study. And, thirdly, there is the exercise designed to give experience in the method and techniques of experiment. All three are an important part of a complete course of study in the experimental method.

Returning then to Bacon's views, experiment, like other engineering activities, should be an ordered procedure. It is the purpose of this book to introduce both the design and the organisation of experiment so that it becomes sound engineering practice and consequently economically well justified. The order of the chapters in the book reflect the logical order in which an experiment should be carried out in its entirety. The first step is to plan the experiment in a general way, the second is to consider in more detail how the measurements are to be obtained. The third step is to consider how errors can arise in the measurements and the fourth considers how these errors might be contained. The procedure of experiment must then be thought out. The results have then to be analysed so that both their significance and application can be reasoned. Finally, the transmission of the results must be prepared with care. It is useful to recognise that the procedures set forth here are as valid for the large research programme in a big research establishment as they are for the situation when the superintendent of a group of engineers puts his head round an office door and instructs the occupier to obtain quickly a few extra results from an existing experimental apparatus; or again for the student performing a laboratory experiment: both scales of experiment must be planned for success: planning might take weeks in the former case and five minutes in the latter. The student must develop the habit of pausing for thought before plunging into his set laboratory exercise.

In summary, experiment is an ordered activity which forms a foundation for analytical models of real events. It is these analytical descriptions that the engineer has to create so as to determine his designs: this places experiment in a position of primacy in engineering practice.

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The planning of experiments: part I – general procedures

2.1 General planning

There are two principle aspects to planning an experiment; one is the scientific and technical aspect, and the other is the administrative one. To the engineer, both should be of equal concern, and both are considered here.

2.2 The brief for the experiment

Before any planning is started a brief for the experiment must be drawn up. Such a brief is rarely, if ever, free of constraints set by others. Usually an experimenter is under instructions to do the experiment: even if a free agent in the choice of a subject for investigation there will inevitably be limitations which, most commonly, are of financial cost.

The onus is always on the experimenter to be quite clear about the brief that has been set. He must be satisfied both on the adequacy of the instructions and on the clarity of them. There is an analogy with architectural practice where the onus is on the architect to ensure a clear understanding of the client's brief, and this requires not only an initial briefing, but a continual assessment that both questions and updates the client's needs.

The brief should contain a statement of the overall object of the experiment that is comprehensive and unambiguous.

For an undergraduate laboratory class, the object of the experiment is invariably set quite precisely, because the outcome of the experimental exercise is known beforehand. For an extended experimental project that an undergraduate might do in a final year of study, the outcome would not be known, at least in full, when the objects of the task were drawn up: it is a research investigation. For a post-graduate research programme, the research student is searching out the unknown, and so the object of the investigation can only be set in general terms: but still it must be set and, in this case, it is important that it be reviewed from time to time as the research proceeds. In industrial practice the experiment can extend from such as a simple test to find the weaknesses in a newly designed component, perhaps, for example, a car door lock, up to a comprehensive fundamental research study of what has been called an 'open-ended' investigation, and which, for example, might lead to the discovery of a new plastic material. For all types of experiment the object must be set before planning begins, even though it is recognised that this may not always be possible with great precision and detail, and also with the recognition that it may be significantly amended as the experiment proceeds, or, indeed, even as the planning continues.

The initial brief must also lay down the principal limitations to the programme. An important limitation is the time available. In industry this is usually laid down precisely. It may be that the results are required by a certain date for a design to be finalised, or it may be that an investigator has only a specific period of time available in which to use a large and intensively worked test plant. This, then, is why it is an important part of the exercise of an undergraduate laboratory experiment that the student complete the investigation in the time allotted. It is important to realise that in engineering practice the time allocated will include the period necessary to complete the investigation by presentation of the results in the required form; the nature of this form is all part of the initial brief: for an engineer in industry on a short investigation, his superior may require only a graph or a table of results; for the post-graduate research student, a complete thesis in a standardised form is required. The preparation of both, however, must be completed within the time set. It can be a salutary exercise for the undergraduate to be required occasionally to produce the results of his experiment in a specified form within the period of his laboratory class.

The other principle limitation to be set in the brief is the financial cost: this includes the cost of the man-power available. For the student this can be represented by the amount of material and equipment available to him; and for the undergraduate by the number of persons in his laboratory group; and for the post-graduate student by the assistance available from technicians. Always some overall limit is set, and often this is separated into a limitation of man-power and a restriction of the other financial costs.

In summary, then, for all types of experiment the researcher must satisfy himself that the brief set is adequately detailed and precisely phrased: these terms of reference must be both suitably comprehensive and unambiguous.

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2.3 The information search

The undergraduate will always precede experiment by a search for information: this usually simply consists of reading a prepared document describing his set experiment. The post-graduate research student will be set to read most of the existing literature that is directly relevant to his allotted subject. He will also question his supervisor, and this latter approach in engineering practice in industry is a most valuable one. Even if a professional engineer seeks advice from a colleague in the next office, with suitable past experience, he is gaining information in a most competent and effective way.

A search for information at this early stage, after the brief has been set, is a most important part of research. So much information has been published in the past, that often an item of great relevance has been effectively lost in the multitude of research reports and papers. Time and again there are cases of work being done that turn out to duplicate, sometimes in part, often almost in the whole, work done long ago: such waste of resources and hence of money is bad engineering.

Much can be done to avoid this these days. Enormous data and information banks on computers exist now, even accessible internationally by direct links. Large abstract publications are produced in many disciplines and some that have long existed are now widely available. They include:

(a) *Engineering Index;*
(b) *Chemical Abstracts;*
(c) *Physics Abstracts;*
(d) *Science Citation Index.*

These four publications are included in the Computer Data Bank of the Lockheed Corporation of the USA. This is on direct access to most large libraries in Europe and North America and it contains some two to three hundred data bases on line.

In addition, for the very latest work, there are lists of contents in recent publications: one such is

(a) *Current contents*

A most valuable source is the *Science Citation Index*. This lists the authors of works, and those papers that have referred to their works. Thus if a person is known to have written about a topic to be investigated by the experimenter, then the latter can trace other works on this subject. This can often be a valuable way of composing a list of relevant reports.

In preparation for such activity in his later professional career, the student should adopt the laudable practice of doing at least some background reading in his text books before starting a laboratory exercise.

As soon as the graduate enters the engineering profession, he can, usually with great long-term profit, start compiling a subject index to cover the topics of his work. A card index is the most convenient form as it is flexible enough to cope with expansion and changes of subject interest as a career progresses. It must also be flexible in the arrangement of subject divisions to cope with these developments: a simple numbering system is best, but the so-called decimal system, as often used in libraries, whereby each subject level is divided into exactly ten classes, is to be avoided as being quite inflexible; it is a clear example of the tail wagging the dog. The subject index then becomes a useful item in the information search when planning an experiment.

From the briefest questioning to the most extended reading, the information search is an essential prerequisite for assessing how the initial brief might best be met. If, indeed, in industrial practice it results in a decision that the proposed experiment is not needed because the knowledge sought already exists, then this is highly effective engineering practice.

2.4 The scientific plan

The variables to be adjusted in an experiment are to be chosen with care; but it can be equally important, for certainty of the final results, that those variables not controlled are also listed, and the significance of their omission appreciated.

When listing experimental variables, clear distinction must be made between dependent and independent variables. Making this distinction is not always straightforward, and so this matter is discussed in more detail in Section 4.2.

The extent of the list of independent variables controls the extent of the experimental programme. If n experimental readings are to be taken of each of m variables, the total number of readings is $2n^{(m-1)}$: then an experimental programme of this nature can soon get out of control. Even the undergraduate, at this stage in planning the operation of his undergraduate experiment, should assess the amount of data that he is required to collect: on occasions, for example, a student will produce a graph of results in the form of a straight line through an origin with some 15 experimental points on it; this is not competent experimentation.

It is helpful to draw up an order of priority of importance of the independent variables, and this can require considerable physical insight into the phenomenon being studied. Here again, prior knowledge from the information search can be invaluable.

There are two powerful techniques for controlling the extent of an experimental programme for a specified number of variables. These are the use of statistical design of experiments and that of dimensional analysis. Both are described in detail in the two following chapters.

Having listed the independent variables, the ranges of them to be covered by the experiments must be decided. This again has a direct effect on the scale of experimentation through the number of readings to be taken.

Linked with the choice of the number and the range of variables is the distinction between two types of experiment, as follows:

(a) *The repeatable experiment:* an example of this is a test of the properties of a material within its elastic limit. Or, another example is the test to determine the power output and the heating characteristics of an electric motor.
(b) *The destruction test:* an example of this is the test to determine the crash-resistant properties of a car. Or, another example is a test to find the arcing damage in an electrical switchgear.

The difficulty with the destruction test is that variables excluded from the list of those chosen for variation might themselves change from test to test. For example, in a simple fatigue test, the successive samples of material might not be identical in composition, and hence in structural behaviour, to the required precision. This uncertainty of composition then becomes an independent variable which is uncontrolled. In this case, statistical design of the experiments can become invaluable.

Often in an experiment a degree of environmental control is required. Certain tests require a temperature control, such as a creep test of materials. Others require a control of the humidity level when, for example, measuring the electrical resistance of plastic materials. Again, it might be necessary to remove dust and other particles from the atmosphere when, for example, using hot-wire techniques for measuring air velocity. It may be found that it is not feasible to gain the required control of the environment: then one may need to include its relevant properties as independent variables.

At this stage in the planning of a large experiment, a preliminary assessment of both the cost and the time schedule of a programme might be drawn up.

In deciding on the variables to be studied, some insight into the physics of the phenomenon to be studied would be used. This, in part, would have come from the prior literature search. Further careful thought at this stage about the physics can be valuable in deciding the correctness of the judgement over the choice and range of variables, but it should certainly be done before undertaking the next stage of planning the experimental equipment: the experimenter must try to judge, as best he can, the likely nature of the physical processes occurring in his experiment.