Chapter one

introduction

1.1 Preface

The study of experimental methods is a necessary extension of all analytical subjects. A knowledge of the methods of verifying analytical work injects new life and vitality into the theories, and a clear understanding of the difficulties of experimental measurements creates a careful attitude in the theoretician which cannot be generated in any other way.

Because experimentation is so important in all phases of engineering, there is a very definite need for the engineer to be familiar with methods of measurement as well as analysis techniques for interpreting experimental data.

Investigators perform experiments in virtually all fields of inquiry, usually to discover something about a particular process or system. Each experimental *run* is a *test*. More formally, we can define an *experiment* as a test or series of runs in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response. We may want to determine which input variables are responsible for the observed changes in the response, develop a model relating the response to the important input variables and to use this model for process or system improvement or other decision-making.

Experimental techniques have been changed quite rapidly with the development of electronic devices for sensing primary physical parameters and for controlling process variables. In many instances more precision is now possible in the measurement of basic physical quantities through the use of these new devices. Further development in instrumentation techniques is certain because of the increasing demand for measurement and control of physical variables in a wide variety of applications.

Obviously, a sound knowledge of many engineering principles is necessary to perform successful experiments; therefore, the experimentation is so difficult. To design the experiment, the engineer must be able to specify the physical variables to be investigated and the role they will play in later analytical work. Then, to design the instrumentation for the experiment, the engineer must have a knowledge of the governing principles of a broad range of instruments. Finally, to analyze the data, the experimental engineer must have a combination of keen insight into the physical principles of the processes being investigated and a knowledge of the limitations of the data.

Research involves a combination of analytical and experimental work. The theoretician strives to explain or predict the results of experiments on the basis of analytical models. When experimental data are encountered which do not fit into the scheme of existing physical theories, a skeptical eye is cast first at the experimental data and then at appropriate theories. In some cases, the theories are modified or revised to take into account the results of the new experimental data, after being sure that the validity of the data has been ascertained. In any event, all physical theories must eventually rely upon experiment for verification. Whether the research is of a basic or developmental character, the dominant role of experimentation is still present. Physical experimentation is the ultimate test of most theories. In these cases, the engineer must utilize all available experience with the previous devices to design the apparatus for a new application.

The range of experiments is so broad, the experimental background of the engineer must be diverse in order to function effectively in many experimental situations. Obviously, it is quite hopeless and impossible to expect any one person to operate at a high level of effectiveness in all areas of experimental work. The primary capability of a particular individual will necessarily be developed in an area of experimentation closely connected with that person’s analytical and theoretical capability and related interests. The broader the interests of an individual, the more likely it is that individual will develop broad experimental interests and capabilities.

In the past, there have been some engineers who designed devices by trial and error with very little analytical work as a preliminary to the experimentation. There are some older areas of engineering where this technique may still prevail. The engineer should know what to look for before beginning the experiments. The objective of the experiments will detect the accuracy required, expense justified, and level of human effort necessary. For instance, a test of an amplifier for a home music system might be less than a test of an amplifier to be used as part of the electronic equipment in a satellite, and so on.

The engineer is not only interested in the measurement of physical variables but also concerned with their control. The two functions are closely related, however, because one must be able to measure a variable such as temperature or flow in order to control it. The accuracy of control is necessarily dependent on the accuracy of measurement.

It is not enough for the engineer to be able to measure skillfully certain physical variables. For the data to have maximum significance the engineer must be able to specify the degree of accuracy with which a certain variable has been measured. To specify this accuracy, the limitations of the apparatus must be understood and full account must be taken of certain random and/or regular errors which may occur in the experimental data. Statistical techniques are available for analyzing data to determine expected errors and deviations from the true measurements. The engineer must be familiar with these techniques in order to analyze the data effectively.

Frequently, the engineer collects the data randomly, many of which are not needed for later analysis. Certain ranges of operation are not investigated thoroughly enough, resulting in the collection of data. The engineer must be sure to take enough data but should not waste time and money by taking too many. The experiments should be carefully planned. Most experimentalists do indeed plan tests with respect to the range of certain variables that they will want to investigate. But they often neglect the fact that more data points may be necessary in certain ranges of operation than in others in order to ensure the same degree of accuracy in the final data evaluation. The anticipated methods of data analysis should be taken into account in planning the experiment, just as one would take into account certain variables in designing the physical size of the experimental apparatus. The engineer should always ask the question: How many data do I need to ensure that my data are not just the result of luck?

Experimentalists do not realize that one simple instrument may not work and thus spoil the experiment. Once this instrument is functioning properly, another may go bad, and so on. They try to solve all problems at once and vary many parameters at the same time.

1.2 Why experiments?

As an example of an experiment, suppose that a metallurgical engineer is interested in studying the effect of two different hardening processes, oil quenching and saltwater quenching, on an aluminum alloy. Here the objective of the experimenter is to determine which quenching solution produces the maximum hardness for this particular alloy. The engineer decides to subject a number of alloy specimens or test coupons to each quenching medium and measure the hardness of the specimens after quenching. The average hardness of the specimens treated in each quenching solution will be used to determine which solution is best.

As we consider this simple experiment, a number of important questions come to mind:

1. Are these two solutions the only quenching media of potential interest?
2. Are there any other factors that might affect hardness that should be investigated or controlled in this experiment (such as, the temperature of the quenching media)?
3. How many coupons of alloy should be tested in each quenching solution?
4. How should the test coupons be assigned to the quenching solutions, and in what order should the data be collected?
5. What method of data analysis should be used?
6. What difference in average observed hardness between the two quenching media will be considered important?

All of these questions, and perhaps many others, will have to be answered satisfactorily before the experiment is performed.

Experimentation is a vital part of the *engineering method*. Consider that x_s are controllable variables and z_s are uncontrollable variables affect the output y want to be observed (although they may be controllable for purposes of a test). The *objectives* of the *experiment* may include the following:

1. Determining which variables are most influential on the response y.
2. Determining where to set the influential x_s so that y is almost always near the desired nominal value.
3. Determining where to set the influential x_s so that variability in y is small.
4. Determining where to set the influential x_s so that the effects of the uncontrollable variables z_s are minimized.

Some applications of experimental design in engineering design include:

1. Evaluation and comparison of basic design configurations.
2. Evaluation of material alternatives.
3. Selection of design parameters so that the product will work well under a wide variety of field conditions, that is, so that the product is robust.
4. Determination of key product design parameters that impact product performance.
5. Formulation of new products.

1.3 Principles of experimental design

The three basic principles of experimental design are; *randomization*, *replication*, and *blocking*. Sometimes we add the *factorial principle* to these three. *Randomization* is the cornerstone underlying the use of statistical methods in experimental design. By randomization we mean that both the allocation of the experimental material and the order in which the individual runs of the experiment to be performed are randomly determined. For example, suppose that the specimens in the hardness experiment are of slightly different thicknesses and that the effectiveness of the quenching medium may be affected by specimen thickness. If all the specimens subjected to the oil quench are thicker than those subjected to the saltwater quench, we may be introducing systematic bias into the experimental results.

By *replication* we mean an independent repeat run of each factor combination. Replication would consist of treating a specimen by oil quenching and treating a specimen by saltwater quenching. Thus, if five specimens are treated in each quenching medium, we say that five replicates have been obtained. Each of the 10 observations should be run in random order. Replication has two important properties. First, it allows the experimenter to obtain an estimate of the experimental error which becomes a basic unit of measurement for determining whether observed differences in the data are really statistically different. Second, if the sample mean (average) is used to estimate the true mean response for one of the factor levels in the experiment, replication permits the experimenter to obtain a more precise estimate of this parameter.

There is an important distinction between *replication* and *repeated measurements*. For example, suppose that a silicon wafer is etched in a single-wafer plasma etching process, and a critical dimension (CD) on this wafer is measured three times. These measurements are *not replicates*; they are a form of repeated measurements, and in this case the observed variability in the three repeated measurements is a direct reflection of the inherent variability in the measurement system or gauge and possibly the variability in this CD at different locations on the wafer where the measurement were taken. Replication reflects sources of variability both *between* runs and (potentially) *within* runs.

Blocking is a design technique used to improve the precision with which comparisons among the factors of interest are made. For example, an experiment in a chemical process may require two batches of raw material to make all the required runs. Generally, a block is a set of relatively homogeneous experimental conditions. Then the experimenter divides the observations from the statistical design into groups that are run in each block.

1.4 Nature of the experimentation

1.4.1 Experiment

A study in which the conditions are deliberately (and usually randomly) assigned by a researcher to individuals/objects/time slots for the purpose of seeing the effect that these assigned conditions have on some characteristic. The assigned conditions are called *treatments*. The characteristic is called the *response* variable. The individuals or objects are called the *experimental units*.

1.4.2 Observational Study

A study in which the conditions are not assigned/controlled by the researcher but simply observed. The conditions are inherent characteristics of the subjects/objects/time slots. Interest still lies in comparing the groups defined by the conditions in terms of the response variable.

For example, do people take longer when someone is waiting for them as compared with no one waiting? Suppose a researcher does a study by observing people getting into their cars in a university parking lot. The researcher records whether or not someone is waiting to obtain the parking spot and also how long it took the driver leaving to depart. The response variable is the amount of time to depart from the time that the person stopped into his/her car until s/he moved forward. This is not an experiment. It's an observational study because the conditions "someone waiting" and "someone not waiting" are not assigned by the researcher but observed.

1.5 Variables in the experiments

A variable is a characteristic of a person or object that varies from person to person or object to object. So examples of variables are height, weight, speed, material, size, shape, number, and etc.

In some experiments, the treatments are one-dimensional and are the values of a single variable called the *factor* in the study. The values or levels of the factor such as: low, medium, and high are called the *treatments*. The purpose of an experiment is to determine if the factor affects the response variable. However factors can be quantitative, such as dose level of a drug.

Treatments in a two-factor study refer to the combinations of levels of the two factors. An *extraneous* variable is a variable not of main interest in the study but believed to be associated with the response variable.

1.6 What's affecting the response variable?

Extraneous variables in an experiment are important to recognize and control since differences on the response variable across the treatment groups may be the result of extraneous variables, not the factor of interest.

The variation in values of the response variable for identically treated runs is referred to as *experimental error*. So maybe the slight differences seen in yields *between* the two groups are not due to factor of interest, but are actually due to variation resulting from *extraneous* variables or due to *experimental error*.

In order to judge whether treatments really differ, it is necessary to have some idea of expected differences in groups simply due to experimental error. Methods of Analysis of Variance are concerned with the measurement of differences between treatment groups, measurement of differences within treatment groups, and the relative comparison of the two types measurements. There are various sources of experimental error*, such as natural variation in experimental units, inability to identically treat the units in the same group, inability to measure precisely*. In general all extraneous variables contribute to experimental error. A *systematic effect* of an extraneous variable would be an effect which generally goes one way: for or against a particular treatment.

1.7 Simple comparative experiments

We consider experiments to compare two *conditions* (sometimes called *treatments*). These are often called simple *comparative experiments*. We begin with an example of an experiment performed to determine whether two different formulations of a product give equivalent results.

Assume an engineer is studying the formulation of a Portland cement mortar. He has added a polymer latex emulsion during mixing to determine if this impacts the curing time and tension bond strength of the mortar. The experimenter prepared 10 samples of the original formulation and 10 samples of the modified formulation. We will refer to the two different formulations as two treatments or as two levels of the factor formulations. When the cure process was completed, the experimenter did find a very large reduction in the cure time for the modified mortar formulation. Then he began to address the tension bond strength of the mortar. If the new mortar formulation has an adverse effect on bond strength, this could impact its usefulness.

1.8 Guidelines for Designing an Experiment

1. Recognition and statement of the problem
2. Selection of the response variable
3. Choice of factors, levels, and ranges

Pre-experimental planning

4. Choice of experimental design
5. Performing the experiment (manufacturing)
6. Statistical analysis of the data
7. Conclusions and recommendations