

CHAPTER IV

INSTRUMENTS AND MEASURING DEVICES

SECTION 40. GENERAL

The present chapter will be limited to instruments and devices of specific interest in fatigue testing, and will not include instruments for general purposes, even if actually used in fatigue experiments. This means that the measurement of variable quantities will be the main point. The complete information about a variable quantity consists of a record of the time curve, but in many cases it may suffice to measure a maximum, minimum or mean value, sometimes with the addition of a frequency, assuming the curve to be sinusoidal. Lack of space prevents giving a detailed description of the various instruments, but references to such information and examples of actual applications will be given.

Instruments and devices may be classified according to many different principles, but the attitude taken here will be the same as indicated in the preceding chapter, namely, that of the investigator who knows his specific purpose and wishes to find out what means will be the best for him to use.

From this starting-point, the first-order division will be based on the quantity which has to be measured, i.e. a displacement, a load, etc., and the second-order division will be based on the design characteristic, i.e. mechanical, electrical, optical, etc.

The present chapter will be divided into the following Sections: (40) General; (41) Displacement-measuring instruments and devices; (42) Strain-measuring instruments and devices; (43) Load-measuring instruments and devices; (44) Stress-measuring instruments and devices; (45) Instruments and devices for determining surface conditions; (46) Instruments and devices for detecting cracks, flaws, and inhomogeneities; (47) Instruments and devices for counting numbers of stress cycles.

Each Section is subdivided into paragraphs according to design features.

Comprehensive reviews and accounts of various instruments and methods will be found in the books mentioned below.

References: PFLIER (1940), ROBERTS (1946), SIEBEL (1958).

SECTION 41. DISPLACEMENT-MEASURING
INSTRUMENTS AND DEVICES

41.0 General

"Displacements", which will be the subject of the present section, may be defined as changes of distance between two points belonging to different objects, whereas "strains", which will be the subject of the subsequent

section, may be defined as changes of distance between two points belonging to the same solid body.

One of the points in a displacement is a moving point and the other is a fixed reference point. An example of such a displacement of interest in fatigue testing is the extension of a coil spring, where one end is displaced and the other is fixed to the framework. Another quantity of interest is the amplitude of vibration. The amplitude is, in fact, a difference between two displacements of the same point at different times in relation to a fixed point, and may be obtained as the result of two displacement measurements, but there are also methods of eliminating the fixed point and measuring the amplitude directly without defining a reference point.

Displacements and amplitudes of vibration may be measured by means of mechanical, electrical, optical, acoustical, and pneumatic devices.

A thorough review including all types of instruments for measuring displacements is presented by Huggenberger and Schwaigerer in the handbook by SIEBEL (1958).

Reference: SIEBEL (1958, 379-395).

41.1 Mechanical Instruments and Devices

A frequently used, simple instrument for measuring displacements is the mechanical dial gauge with ranges from 5 to 50 mm and an accuracy of from 1 to 20×10^{-3} mm. Another simple device is the micrometer screw. It may be mentioned that the accuracy of this simple tool can be considerably improved by indicating electrically the contact between the anvil of the screw and the metallic object to be measured by means of a micro-ammeter or a neon lamp which glows when a circuit is completed. Accuracies better than 10^{-3} are easily obtained. Still greater accuracy can be attained by a purely mechanical device used in the proving ring for measuring static loads (cf. Section 43): a vibrating reed consisting of a thin strip with a small mass attached to its free end is set vibrating by hand; when the anvil of the screw makes a very slight touch on the object, a typical sound is heard and the damping of the reed is considerably increased. The amplitude should decline from $\frac{1}{2}$ in. to zero in 2 or 3 seconds. The accuracy will then be about 0.25 to 0.50×10^{-3} mm.

The reed gauge, designed primarily for determining static loads by means of the proving ring, may also be used for recording the peak response to a transient motion of systems of single degrees of freedom as described by RUBIN (1958). The recorded data permit the calculation of peak response in each vibrational mode of a complex structure. An upper bound to the maximum structural response can be obtained by summing the peak responses in each of the modes. The error thus introduced is in many cases of small significance.

The micrometer can be used not only to measure displacements and amplitudes of vibrations but also for pre-setting and maintaining constant amplitudes of vibrations within narrow limits, as has been successfully practised by DOLAN (1951).

References: DOLAN (1951), RUBIN (1958), NBS Circ. 454.

41.2 Electrical Instruments and Devices based on Measurement of Resistance, Inductance, or Capacitance

The simplest method of converting a displacement into an electrical quantity is by means of a contact sliding on a high-resistance wire incorporated in a conventional Wheatstone bridge. The alternating output of the bridge is measured by an amplifier and valve voltmeter of a recording instrument. Various designs of this device are described by Huggenberger and Schwaigerer in the hand-book edited by SIEBEL (1958). An accuracy of ± 1 per cent over a range of 50 mm is obtainable.

An improvement is obtained by substituting a potentiometer for the wire. Commercial devices, called resistor transducers, are now available. An application of such a transducer is described by KENNEDY and SLADE (1956). A movement of 0.001 in. over a total range of 0.5 in. could be detected.

Another type of resistance transducer may be easily produced using a resistance strain gauge (which will be discussed in the subsequent section) and an elastic member—a bending bar or a ring. Within certain limits, there is a linear relation between the strain and the displacement which, by the use of an appropriate shape and dimensions of the elastic member, can be varied within wide ranges.

Large transient displacements have been recorded by WEIBULL (1948), using unbonded resistance strain gauges within the plastic range. It was found that the resistance of wires from certain materials could be calculated from the geometrical configuration on the assumption of a constant volume. Each wire can only be used once, of course. It is also to be noted that there is a limit to the speed which can be recorded, due to the fact that the velocity of plastic waves is lower than that of elastic waves.

The resistance incorporated in the bridge may also be replaced by an inductance or a capacitance related uniquely to the displacement, the advantage being that the displacement of the object can be measured without touching it or loading it by additional masses. This is important when systems with small masses and weak springs are concerned. In these cases, the capacitance method is the better, because no extraneous forces are imposed on the system. Another advantage is that the sensitivity can be made extremely high by using advanced circuits.

An interesting application of the capacitance method is reported by RUSHFORTH and SELWOOD (1958). A moving-coil vibrator was held close to a vibrating structure and driven electrically so that the vibrator oscillated in sympathy with the structure. This condition was checked by measuring the electrical capacitance between two plates, one formed by the structure itself, and one mounted at the tip of the vibrator shaft. The amplitude and phase of the current driving the vibrator were adjusted until this capacitance became constant. Any type of vibration amplitude pick-up may be fixed to the vibrator shaft without affecting the vibrating structure. In a particular case, vibration amplitudes up to 0.030 in. were measured with good linearity and reproducibility, with a resolution of about 0.0001 in.

References: RUSHFORTH and SELWOOD (1958), SIEBEL (1958, 385-390), WEIBULL (1948).

41.3 Photo-electric Instruments and Devices

A versatile method of measuring displacements and controlling amplitudes of vibration within wide ranges and with extremely high sensitivity and accuracy is obtained by combining commercial photo-tubes and screens, mirrors or the like. This method has the same advantage as the capacitance method that the measuring device does not impose any force or disturbance on the moving system. The measuring device is arranged according to the requirements of the individual problem.

41.4 Optical Instruments and Devices

An extremely simple device for measuring the amplitude of a vibrating system is the vibrograph, which consists of a diagram of two sloping lines fastened to the vibrating mass. The apparent movement of the point of intersection of these two lines is a measure of the amplitude, being horizontal if the amplitude is vertical. The accuracy is increased to a certain extent by decreasing the angle between the two lines.

Another simple optical method of measuring amplitudes of vibrating specimens is by means of a telemicroscope viewing the band of light produced by a polished edge of the specimen which is illuminated by a point source of light, or by viewing a mark on the specimen which is seen as a line when vibration occurs. An accuracy better than 1 per cent is easily obtained.

41.5 Pneumatic Instruments and Devices

Pneumatic instruments have been designed to give an extremely high magnification of the displacement. These could easily be arranged for measuring displacements, but as they are mainly intended for strain measurements they will be discussed in the next section.

SECTION 42. STRAIN-MEASURING INSTRUMENTS AND DEVICES

42.0 General

Strain is defined as the change of distance between two points belonging to the same object. Within the elastic limit of the material under consideration, the stress is proportional to the strain according to Hooke's law and, therefore, strain measurements generally have the purpose of determining the stresses within the specimen.

As the strain is equal to the increase in length divided by the length itself it is apparent that the accuracy increases with the gauge length, provided that the stress distribution is uniform. In a notched specimen, where stress concentrations appear, the gauge length must be reduced, if it is desired to determine the maximum stress. The gauge length varies from 0.5 to 1000 mm in devices commercially available, some of them having adjustable or interchangeable values.

Because of the importance of determining stresses accurately and reliably, a great variety of strain-measuring instruments and devices have been devised. Most of them have been developed to satisfy the requirements of

static testing, and many of them are unsuitable for measuring variable strains, generally due to the way in which the strain gauge is attached to the specimen, but also because of the low natural frequency of the spring system composed of the masses and flexible members. This section will be restricted to instruments and devices suitable for measuring variable strains.

References: FINK (1952), HUGGENBERGER and SCHWAIGERER (1958), LEHR (1940).

42.1 Mechanical Instruments and Devices

Most of the mechanical strain gauges are attached to the specimen by means of knife edges, which cannot withstand vibrations. This is easy to understand, considering the fact that a very large magnification of the displacement is necessary. Conventional gauges have magnifications of from 300 to 3000. The limit appears to be 4000 for purely mechanical instruments.

If the strain gauge is fastened to the test piece appropriately, however, it is possible to measure strains of moderate frequencies by means of mechanical gauges. This method has been applied to locomotive connecting rods by LEHR (1938), and to freight motor cars by LEHR and SCHULZ (1942).

The difficulties are lessened, of course, if the instrument is required not to give the transient value of strain, but to indicate when a pre-assigned value is reached and to count how many times this event has occurred during a given period. Such an instrument was designed and constructed by THUM and SVENSON (1944), and a further improvement resulting in a practical and reliable instrument was made by SVENSON (1952). This instrument is fastened rigidly to the machine part by two welded bolts and nuts, the distance between them being the gauge length. At a certain strain, which can be pre-set by means of a micrometer screw, a lever completes an electrical circuit and a counter is actuated. With a gauge length of 25 mm it is possible to measure strains of 0.002 per cent.

Another counting strain gauge applied to aircraft structures is described by LAMBIE (1952).

References: LAMBIE (1952), LEHR (1938), LEHR and SCHULZ (1942), SVENSON (1952), THUM and SVENSON (1944).

42.2 Electrical Instruments and Devices based on Measurement of Resistance

The most versatile strain gauges are the electrical ones, and in particular those based on a change of the resistance. They are easily cemented to the specimen without adding a discernible mass, and there is practically no limit with regard to the frequency. The accuracy is satisfactory provided proper care is taken.

The current use of resistance strain gauges consists in attaching one or more strain gauges (in some cases several hundreds) to the test piece or structure. The strain gauge is then incorporated in a conventional Wheatstone bridge circuit and the alternating output is amplified and measured by a valve voltmeter.

An improvement was introduced by GROVER (1943) who substituted a cathode ray tube for the voltmeter. The strain-gauge bridge was balanced with a potentiometer and the output voltage observed on the screen, thus permitting the determination of maximum, minimum and mean values of the periodically varying strain. A similar null method was further developed by LITTLEWOOD and MASKERY (1953).

Some of the disadvantages observed were eliminated by GUSTAFSSON and OLSSON (1956) by introducing a switch which shorted the output voltage from the bridge except during a short interval determined by a synchronizing device. When the switch is closed there is no input voltage to the cathode ray tube and a straight line is visible on the screen. The bridge is balanced by an accurate potentiometer. Each reading of this potentiometer corresponds to a certain resistance of the strain gauge, and it is thus possible to determine the extreme values with an accuracy that is almost entirely dependent on the accuracy of the calibration and the quality of the potentiometer. With properly applied strain gauges of good make an accuracy of 0.1 per cent was attained. The sensitivity was high and with suitable gauges strains of less than 1×10^{-6} could be detected.

The strain-gauge technique is now well developed. Reviews are given by BALL (1945), WORLEY (1948), and HEMPEL and FINK (1952), and a collection of strain gauge bridge formulae is presented by SCOTT (1957c). Methods of installation, calibration, test procedure and recording are described by KRAUSE (1957). Strain measurements during fatigue tests are reported by GISEN and GLÖCKER (1938) and in connexion with structures by SCHWAIGERER (1952).

The results from strain-gauge measurements are in general reliable but, in some makes, a long-time drift of considerable magnitude has been observed as reported by SCOTT (1957a,b). Another disadvantage is the low resistance to repeated strains. An amplitude of 0.2 per cent corresponds to a fatigue life of a few thousand strain cycles. It is, however, possible to mount the strain gauge on a portion of the specimen where the cross-section is larger than the critical section, or to use a tension bar in series with the test piece.

For a single measurement, strains of several per cent may be recorded as demonstrated by WEIBULL (1948) and by SVENSON (1953).

References: BALL (1945), GISEN and GLÖCKER (1938), GROVER (1943), GUSTAFSSON and OLSSON (1956), HEMPEL and FINK (1952), KRAUSE (1957), LAMBIE (1952), LEHR (1938), LEHR and SCHULZ (1942), LITTLEWOOD and MASKERY (1953), SCHWAIGERER (1952), SCOTT (1957a,b,c), SVENSON (1953), THUM and SVENSON (1944), WEIBULL (1948), WORLEY (1948).

42.3 Optical Instruments and Devices

Very sensitive gauges have been developed in which the magnification is achieved by means of mirrors, but in general these are unsuitable for measuring variable strains. The classical device is the Martens mirror extensometer. An investigation of the accuracy of this device regarding its use in fatigue tests has been carried out by WIZENEZ (1937).

Reference: WIZENEZ (1937).

SECTION 43. LOAD-MEASURING INSTRUMENTS AND DEVICES

43.0 General

Load-measuring instruments and devices are, with few exceptions, based on the deformation of an elastic body—a bar or a ring—and its deformation is converted by mechanical, electrical, hydraulic or optical means into a deflexion of a needle or an index-finger.

Descriptions of instruments based on various principles are given by Ermlich and Hengemühle in the hand-book edited by SIEBEL (1958).

Reference: SIEBEL (1958, 272–314).

43.1 Mechanical Instruments and Devices

A simple device designed primarily for determining static loads is the Morehouse proving ring, which consists of an elastic steel ring and a micrometer for measuring the deflexion of the ring.

The unmodified ring can be used for dynamical calibration, but the value of the reed (described in Section 41) as an indicator is considerably reduced, and errors may be appreciable at certain critical testing speeds. Sonntag Scientific Corp. first overcame this difficulty by replacing the reed with an electrically insulated, spring-loaded plunger having a single indicator contact. When the anvil of the micrometer screw contacts the lower end of the plunger, a circuit is completed and a neon lamp glows. By introducing a spring-loaded plunger having double contacts for indicating purposes, both maximum and minimum load in tension or compression could be measured according to a design by THURSTON (1948).

A survey of instruments and methods for measuring variable loads is given by ERKER and SVENSSON (1951).

Loads produced by inertia forces are measured by accelerometers. As these loads are of considerable importance in aircraft design, several types of accelerometer have been developed, some of them recording and some counting. Of the first type may be mentioned one described by RIDLAND (1954). The development of a counting accelerometer is reported by JOHNSON (1955); this is called a unitized statistical accelerometer, and responds to an arbitrarily pre-set level of acceleration. Its size is only one cubic inch, and a number of such counters can therefore be easily put together on one assembly. It is very accurate up to 20 c/s.

References: ERKER and SVENSSON (1951), JASPER (1952), JOHNSON (1955), RIDLAND (1954), THURSTON (1948).

43.2 Electrical Instruments and Devices

43.21 Based on measurement of resistance.—The advanced technique of electrical resistance strain gauges is easily applied to load measurements by attaching the strain gauges to a tension, bending, or torque bar; for the calibration of fatigue testing machines these should preferably be of the same shape as the test specimen. The strain gauges may

themselves be calibrated by means of static dead-weight machines. The accuracy of such a device as examined by RUGE (1956) is better than 0.4 per cent for a load of 1400 tons and better than 0.3 per cent for a load of 450 tons. Descriptions of such devices are given, for example, by PISCHEL (1953) and by MOODY and DENEHY (1954).

Conventional resistance strain gauges consist of metallic wires. The change of resistance is very small, which necessitates a high amplification involving difficulties and uncertainties (three stage amplifiers with a gain of 5×10^5 may be needed). Semi-conducting materials are considerably much more sensitive, although less reproducible. Such a piezo-resistive material is the *n*-type germanium which has been used by MASON and THURSTON (1957) for the measurement of displacement, force, and torque. The properties of this material for strain gauge purposes are discussed in the paper, and a torsional transducer is described and the voltage-torque characteristic is given.

References: MASON and THURSTON (1957), MOODY and DENEHY (1954), PISCHEL (1953), RUGE (1956).

43.22 Based on measurement of inductance or capacitance.—Several designs based on these principles have been made. The objections when applied to strain gauges, mentioned previously, are less severe because the heavy masses incorporated in the instrument are compensated by the rigidity of the bar. High-frequency load cycles can therefore be measured and recorded. A capacitive dynamometer has been designed and constructed by CARTER, SHANNON and FORSHAW (1945), and another by FRANK and GIBSON (1954).

References: CARTER, SHANNON and FORSHAW (1945), FRANK and GIBSON (1954).

43.3 Piezo-electric Instruments and Devices

The conventional piezo-electric material has for many years been quartz, which is very reliable and constant with excellent insulation properties. In more recent years, barium titanate has been much used. It is much more sensitive, and has the added advantage of allowing complicated shapes of gauge to be used.

Piezo-electric gauges are not particularly suitable for measuring static loads, but are very convenient for measuring variable loads and shock waves. In the case of quartz, reflections from the housing, obscuring the measurements, can be effectively eliminated by making the housing of duralumin or lead, since the acoustic impedances of these materials are very close to that of quartz in the longitudinal direction. As an example of such a pressure box gauge, reference is made to a paper by EDWARDS (1958). A small barium titanate transducer for aerodynamic or acoustic pressure measurements is described by WILLMARTH (1958) and other descriptions are given by MARK and GOLDSMITH (1955) and RIPPERGER (1954).

References: EDWARDS (1953), MARK and GOLDSMITH (1955), RIPPERGER (1954), WILLMARTH (1958).

43.4 Optical Instruments and Devices

A very straightforward and reliable dynamometer is obtained by measuring the deflexion of a bar or proving ring by means of a microscope. Both the maximum, minimum and mean loads may be accurately determined independently of the frequency.

The use of mirrors and telemicroscopes in conjunction with proving bars is particularly simply applied to a torque bar, and accuracies better than $\frac{1}{4}$ per cent may be attained. It is also possible to measure the torque at an arbitrary point in the load cycle while the machine is running at full speed, as described by CROSSLAND (1956). The method consists of fitting a contact breaker on the driving shaft. By placing this breaker at a desired angular position, a stroboscope illuminates the scale which is used in conjunction with a telescope and mirrors on the torque bar. The torque at this point of the cycle may thus be measured and the maximum and minimum torque is easily found by turning the breaker until a maximum or minimum value is observed.

Reference: CROSSLAND (1956).

SECTION 44. STRESS-MEASURING INSTRUMENTS AND DEVICES

44.0 General

Stresses may be determined indirectly by measuring strains and computing the stresses from known constants of the material. This method only works within the elastic range of the material, and requires a knowledge of the strains in three directions. When surface stresses are concerned this requirement reduces to two directions, as the stress component perpendicular to the surface is zero.

Conventional strain gauges measure the strains (and thereby the stresses) at discrete points of the specimen only. An overall and continuous picture of the state of strains, suitable for calculating the corresponding stresses, is obtainable by photoelastic analysis. By analogy and with due consideration of the constants of the materials, the stresses in specimens of identical shape but made from non-transparent material may be determined.

A more direct method of stress determination is obtained by use of X-ray diffraction methods. These methods are also applicable to the measurement of residual stresses.

Thus the only methods of stress determination requiring specific instruments are the photoelastic method and the X-ray diffraction method, and these will be discussed below.

44.1 Optical Instruments and Devices

A detailed picture of the stress distribution in test pieces of complicated shapes, impossible to obtain by measuring the strains at discrete points, results from photoelastic analysis. The basis of this well-developed technique is quite easy, but it requires a good deal of experience and the numerical evaluation of experimental data is rather time-absorbing. The practical

application of this analysis to design problems is discussed by HORGER (1938). Of recent publications valuable investigations are presented in the Proceedings of the Congress of Photoelasticity and Photoplasticity in Brussels (1954). A new material for three-dimensional photoelasticity is described by LEVEN (1948) who also reports investigations of the properties of the material fosterite at elevated temperatures (LEVEN, 1949) and of stresses in keyways. The stress distribution around rivets has been examined by SMITH and ZANDMAN (1957). Finally reference is made to a comprehensive survey of apparatus and methods by Föppl and Mönch in the hand-book edited by SIEBEL (1958).

A technique giving similar, even if not very precise, results is the brittle lacquer method, which is a useful and easy way of locating danger points in the test piece. Some developments and applications are described by LINGE (1958).

OKUBO (1953) has reported that surface stresses may be determined by means of electroplating. He found that the colour deepens with increasing number of cycles.

References: BALLET and SALMON-LEGAGNEUR (1954), FÖPPL and MÖNCH (1958), HORGER (1938), LEVEN (1948, 1949, 1950), LINGE (1958), OKUBO (1953), SMITH and ZANDMAN (1957).

44.2 X-ray Instruments and Devices

The X-ray diffraction method is capable of measuring the stresses produced by external loads as well as residual stresses existing in unloaded specimens. Two different exposure methods are described in the Handbook of Experimental Stress Analysis, John Wiley (1950) and by BARRETT (1943). A comprehensive survey of apparatus and methods of stress evaluation is given by Glocker in the handbook edited by SIEBEL (1958).

References: GLOCKER (1958), SIEBEL (1958, 575-608).

SECTION 45. INSTRUMENTS AND DEVICES FOR DETERMINING SURFACE CONDITIONS

45.0 General

The important influence of the surface condition on the fatigue life has been known for a long time, and, accordingly, numerous methods for the examination of surfaces from a fatigue testing point of view and for correlating the results to the fatigue strength have been proposed. As a recent contribution to this problem may be mentioned a publication by GOMBAUD (1955), in which statistical analysis is applied to the classification of surface finishes.

In spite of the many efforts to correlate surface condition with fatigue strength, and the highly developed technique now available for a detailed examination of the contour and topography of solid surfaces, it must be admitted that the results are not really satisfactory; even if the surface condition is perfectly well known, the precise effect on the fatigue life cannot be predicted with any great certainty.

The methods of determining the surface condition may be either of the destructive or the non-destructive type. The disadvantage of the first

alternative resulting in a destruction of the surface may, to some extent, be compensated by the possibility of studying the structure of the solid beneath the surface.

The various methods now available may be classified as follows: (1) stylus methods; (2) taper sectioning methods; (3) optical interference methods; (4) optical reflection methods; (5) reflection electron microscopy.

A general review of the methods of surface examination has been given by BOWDEN (1956), and in its main points this is followed in the present section.

References: BOWDEN (1956), GOMBAUD (1955).

45.1 Stylus Methods

The contours of a solid surface may be recorded directly by passing a tracer needle slowly over the surface. The stylus is usually a conical diamond with a radius of curvature of down to 2×10^{-4} cm. The vertical movement of the stylus is amplified by mechanical or electrical means. An amplification of up to 40,000 is obtainable. Under favourable conditions, it may be possible to detect scratches which are only 250 Å deep. Accounts of the theory and limitations of this method are presented by REASON, HOPKINS and GARROD (1954), and by UMPHREY (1958).

References: REASON, HOPKINS and GARROD (1954), UMPHREY (1958).

45.2 Taper Sectioning Methods

The irregularities of a surface may be observed directly under a microscope on a cross-section of the specimen cut at right angles to the surface. A magnification of, say, 10 of the irregularities may be obtained by cutting the section obliquely to the surface. In most cases, it is necessary to protect the surface during this operation by electroplating, using a metal of similar hardness (NELSON, 1940). This procedure has been developed, as reported by BOWDEN and TABOR (1954), to such a perfection that irregularities of 10^{-5} cm in height can now be detected.

References: BOWDEN and TABOR (1954), NELSON (1940).

45.3 Optical Interference Methods

The usual method of measuring surface contour by means of two-beam interference has been improved by TOLANSKY (1948). The procedure consisted of coating the surface and the lens with a transparent layer of silver and letting the incident light be reflected back and forth several times. By this improved method, the detection of features in the surface of a height of 25 Å has been made possible.

By a further improvement, using a spectrograph and white light, the sensitivity could be still more increased, allowing the detection of steps and similar features in the surface as small as 6 Å with an accuracy of about 1–2 Å. This method has been developed by COURTNEY-PRATT (1951) and by BAILEY and COURTNEY-PRATT (1955) with remarkable success.

References: BAILEY and COURTNEY-PRATT (1955), COURTNEY-PRATT (1951), TOLANSKY (1948).

45.4 Optical Reflection Methods

The finish of plane surfaces has been studied by JOANNIS (1957) by projecting a beam of light on to the surface at an angle of 30° to the normal. The surface was then rotated about the normal axis and the values of light reflected along the normal were measured. This method does not give any details of the surface, but gives an average value which will be useful in deciding whether directional anisotropy is present or not.

Reference: JOANNIS (1957).

45.5 Reflection Electron Microscopy

The normal but intricate method used in electron microscopy of preparing transparent replicas of the surface is of restricted applicability, and the results are sometimes doubtful. The difficulties can be avoided by directing the electron beam at glancing incidence on to the surface, and focusing the scattered electrons. Extensive investigations of this method have resulted in remarkable results as reported by COSSLETT (1952). The great advantage of this technique is that the surface can be examined directly by the beam and no replicas are necessary, and that it is easy to calculate the true height of the surface features from the long shadows appearing in the picture. This method has been developed to a considerable efficiency in the laboratory of Prof. Bowden, Cambridge, as demonstrated by MENTER (1952, 1953).

References: COSSLETT (1952), MENTER (1952, 1953).

SECTION 46. INSTRUMENTS AND DEVICES FOR DETECTING CRACKS, FLAWS AND INHOMOGENEITIES

46.0 General

As already mentioned in Section 27, there are two different methods of detecting cracks: the non-destructive and the destructive. Only the former will be discussed in this Section, as no specific instruments are required in the latter.

The detection of fatigue cracks is very important in fatigue testing, in that a considerable simplification would result if every fatigue test could be split up into the pre-crack and the post-crack stages. One of the difficulties in doing so, however, is that the first crack very probably starts at an early stage of the fatigue procedure, and its detection depends on the power of the method used. The most powerful method of detecting incipient cracks involves the use of electron microscopy, a technique which requires the destruction of the test specimen.

The methods discussed in this Section will be divided into the following classes: (1) microscopic methods; (2) electrical-resistance methods; (3) eddy-current methods; (4) magnaflux methods; (5) ultrasonic methods.

General reviews of the different methods and corresponding instruments and devices are given by Berthold, Vaupel and Förster in the hand-book edited by SIEBEL (1958), and in the publications listed below.

References: DEMER (1955), SIEBEL (1958, 575–675), TEMPLIN (1930).

46.1 Microscopic Methods

Visual inspection for the detection of fatigue cracks by the naked eye can be improved by several methods such as painting the surface under examination with oil-whiting, fluorescent and dye penetrants, or by bubble or stress-coat methods; even so, to obtain any resolution capacity, the optical or electron microscope cannot be avoided.

In any case, the early detection of a fatigue crack requires experience of the observer and some indication of where to look for the crack. In this respect it may be helpful to localize suspected areas by means of a brittle lacquer.

References: DECK (1956), DURELLI and OKUBO (1954).

46.2 Electrical-resistance Methods

A simple method of detecting incipient cracks in static tests of large specimens, used by POWELL (1946) in static testing, was suggested by Shanley for use in fatigue tests and developed by FOSTER (1947), and is now frequently used when testing full-size aircraft structures. It consists of cementing small insulated wires to the most critical areas of the structure. The crack is then indicated by rupture of the wire, which is incorporated in a suitable circuit. There are, of course, some conditions to be considered with regard to the strength properties and dimensions of the wire. The insulation and the cement are also influential factors. In the paper by FOSTER (1947) the results and comments on the installation technique are given. It was found—as has later been confirmed—that this indication system enables improvements to be made in the accuracy of the results from fatigue tests of both small laboratory specimens and large structural components.

An investigation by MCGUIGAN, BRYAN and WHALEY (1954) to determine the best commercially available combinations of wire types, wire sizes, and cements, showed that of the combinations tested the most sensitive and easiest to apply were 0.002 and 0.0012-in. diameter Formex insulated annealed copper wires. When used with Duco cement, fatigue cracks as small as 0.00022 to 0.00067 in. could be detected.

Another method of detecting cracks based on the measurement of electrical resistance, and which also permits the measurement of the crack depth, consists of two movable contacts at a fixed distance from each other. When pressed against the metallic surface the resistance reveals whether a crack exists or not, and also the approximate depth of the crack. Applications of this instrument are reported in references listed below.

References: BRAND (1957), BUCHANAN and THURSTON (1956), FOSTER (1947), MCGUIGAN, BRYAN and WHALEY (1953), POWELL (1946).

46.3 Eddy-current Methods

Another non-destructive method of detecting cracks is the induction of eddy-currents in the surface layers of the metallic specimen. The technique of such methods is described in a paper cited below.

Reference: KEIL and MEYER (1954).

46.4 Magnaflux Methods

A very sensitive method of detecting cracks at or just beneath the surface of metallic bodies, called the Magnaflux method, consists of applying a magnetic field to the specimen and pouring over it a fluid containing suspended magnetic particles. This method was used for the inspection of coil springs by DEFORREST (1932). Further investigations and developments were made by WEVER and HÄNSEL (1938) and HÄNSEL (1937/38). Theory and practice of magnaflux testing are reported in Serial No. 381, Aug. 2, 1938, Aero. Mat. Lab., Naval Aircraft Factory, Washington.

Further developments are described by HEMPEL (1939), who also applied the method to the examination of coil springs. Correlation of gamma radiography and Magnaflux indications in the inspection of large cast-steel connecting rods was investigated by THOMPSON (1954). It was found that the two methods may serve as a complement to one another.

References: DEFORREST (1932), HEMPEL (1938/39, 1939), HÄNSEL (1937/38), THOMPSON (1954), WEVER and HÄNSEL (1938).

46.5 Ultrasonic Methods

By means of vibrating quartz or barium titanate crystals, elastic waves can be generated and transmitted through solid media. This procedure offers a reliable and convenient method of detecting cracks and flaws or other inhomogeneities in a specimen. There are three different methods possible. The ultrasonic beam may be either transmitted or reflected and, as a third possibility, a resonance frequency may be determined. For crack detection the most useful method is by reflection, because this permits a precise determination of the location of the crack, wherever it be within the test piece.

The theory of elastic wave propagation is developed in a paper by MAPLETON (1952) and the theory of ultrasonic materials testing in a publication by VAN VALKENBURG (1948). Another account is given by DESCH, SPROULE and DAWSON (1946). The instruments required are described by CLAYDON (1958).

For control purposes it may be useful to use test specimens having known defects; this problem has been discussed by THEIS and BARTELD (1954) and a method of producing such specimens by differential strains in layers of brittle materials is described by MILLARD (1955).

Among descriptions of applications may be mentioned those by HAFEMEISTER (1954) in connexion with forging ingots, and by BÖHME (1958) on aluminium test pieces.

The crystal usually serves as both transmitting and receiving probe. In some cases it may be advantageous to use two crystals, one for transmitting the waves and another for receiving them. As an example of such a device, reference is made to an investigation by KENNEDY (1956) carried out for the purpose of studying fatigue of curved surfaces in contact under repeated load cycles. The small test piece, being a steel ball of 2 in. diameter, necessitated small dimensions of the quartz crystals. These operated at a frequency of $2\frac{1}{2}$ Mc/s. The diameter of the two crystals was 6 mm. The

crystals were contained in metal capsules attached to screened leads, and were attached to two flats ground on the surface of the test ball. The ultrasonic beam from the transmitting crystal could be made to strike its flat at any desired angle, depending on the inclination of the capsule in its mounting. The second crystal received an echo signal through the other flat. The attachment of the blocks was accomplished by dissolving some of the resin used for making them in acetone. The resulting bond was found to be very strong and did not interpose any different material between block and ball.

References: BÖHME (1958), CLAYDON (1958), DESCH, SPROULE and DAWSON (1946), HAFEMEISTER (1954), KENNEDY (1956), MAPLETON (1952), MILLARD (1955), THEIS and BARTELD (1954), VAN VALKENBURG (1948).

SECTION 47. INSTRUMENTS AND DEVICES FOR COUNTING NUMBERS OF STRESS CYCLES

47.0 General

The prime objective of a fatigue test is to determine the number of cycles to failure, independent of how failure is defined. For this reason, some kind of counter is an indispensable part of the testing equipment, and in multi-stress level tests it may also have the added function of indicating the moment at which the stress level has to be changed.

In some test procedures, however, it is of interest to know not only the total number of stress reversals during a certain period but also the number of reversals per unit time, i.e. the frequency. This is particularly important when the load imposed on the specimen is produced by inertia or centrifugal forces, or in machines of the resonant type, where a certain percentage reduction in frequency indicates the end point of the test.

If the frequency of the test is constant it does not matter whether the number of cycles is counted or the frequency is measured, because the one can easily be converted to the other. This condition is not always fulfilled, however, particularly at the beginning and in the later stages of the test; accordingly a counter is always needed, and in some cases also some device for measuring the frequency.

47.1 Counters

When the frequency is uniquely determined by the speed of a rotating motor the number of reversals is most easily measured by a revolution counter. Counters of this type may be arranged to control and monitor programme tests. Both mechanical and electrical counters for this purpose are described by BECKER (1950).

In electrical testing machines the numbers of cycles are counted by means of electric clocks, electro-mechanical counters or dekatron selector tubes. An application of the latter instruments is described by MOORE (1956).

It may sometimes be convenient to convert mechanical vibrations into electrical signals, which are then easily counted and used for automatic control.

References: BECKER (1950), MOORE (1956).

47.2 Frequency-measuring Instruments and Devices

The frequency may be measured by means of mechanical instruments, but for this purpose too electrical instruments are more versatile and more suitable for control manipulations which would require complicated mechanisms if performed mechanically.