THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

STRESS DISTRIBUTION IN SPRINGS

A LITERATURE SURVEY

by

M. O'Malley, B.Sc.

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SUMMARY

A search of the literature has shown that of the many methods of stress measurement available, only a few are applicable to measuring stresses in springs - strain gauges, x-ray diffraction, photoelastic, stress relief and ultrasonic methods. All these methods have limitations in their application to measuring stresses in springs. Strain gauges and x-ray diffraction only measure the surface stresses in the test piece, whereas the ultrasonic and stress relief methods measure the average stress through the bulk of the test piece, but none gives any indication of the actual internal stress pattern involved. Photoelasticity will give an indication of the internal stress pattern of a loaded spring, but gives no indication of the residual stresses arising from spring manufacturing processes.

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1. INTRODUCTION

In service, springs are required to perform in some state of stress. This stress is normally a combination of the residual stress present in the spring, and the working stress applied. To ensure that the sum of these two stresses does not result in failure of the spring, an accurate method of measuring the residual stress distribution within the springs is required.

In 1977 work was carried out in conjunction with Sheffield University, measuring the surface stress pattern in hot-coiled springs using strain gauges. However, strain gauges are unsuitable for work at temperatures above ambient, and so some other method for measuring stresses in springs at elevated temperatures is required. It was therefore decided to carry out a literature survey in order to assess the various methods of stress measurement available which are applicable to use with springs. This report is a result of that survey.

2. METHODS OF STRESS MEASUREMENT

There are various methods available for measuring the stresses in a component. These fall into two distinct catagories - destructive and non-destructive testing. It appears, from the literature, that the destructive methods of stress measurement are unsuitable for the measurement of stresses in springs, as most methods involve the removal of a uniform layer of material from the surface of the components, thus producing a measureable change in the shape of the component as stress relief occurs. However, with springs it is impossible to remove a uniform layer of material from the surface.

In most cases, non-destructive stress measurement methods are found to be more suitable for stress determination as they do not render the component inoperable after testing. There are five possible methods of non-destructive stress measurement at the moment, which could be applicable to measuring stresses in springs - stress relieving, strain gauge, photoelastic models, x-ray diffraction and ultrasonic methods. However, all five have severe limitations in their application to measuring stresses in springs.

3. STRAIN GAUGE METHOD OF STRESS MEASUREMENT

3.1. Theory of method

The electrical resistance strain gauge operates on the principle that when an electrical conductor is strained, its electrical resistance varies in proportion to that strain, an extensional strain producing an increase in resistance and a compressional strain causing a decrease. As the strains experienced by most structural materials in their working range are small, the change in resistance of the gauge will also be small, and so to increase the sensitivity, most gauges are produced by looping a length of wire to form a grid.

3.2. Experimental technique

The method normally used to measure the stress in a component using strain gauges involves the use of a Wheatstone bridge network (Fig. 1)(1). Gauge 1 is the active gauge, this is bonded to the component and measures the strain occurring in the component. Gauge 2 is a "dummy" gauge and is bonded to an unstrained piece of material similar to that being tested, thus cancelling any resistance changes which may occur due to temperature changes in the vicinity of the gauges. R_1 and R_2 are standard resistors built into the instrument. Thus, when the active gauge is strained, the galvanometer needle deflects and thus the amount of strain is measured. Knowledge of the algebraic stress-strain relationships allows conversion of the strain readings into a measure of the stress. In most applications, the directions of the principal stress axes in the component are unknown and so the use of a three element gauge rosette is required (Fig. 2)$^{(2)}$. These measure, not only the magnitude of the applied stresses, but also their directions.

3.3. Limitations of strain gauge measurement of stress

One of the main limitations of the strain gauge method of stress measurement is the inability of the gauge to operate at temperatures above ambient, due to the resistivity of the wire changing with changing temperature. Research is being carried out into a gauge which will operate at elevated temperatures, but at the present moment the accuracy of such a gauge is debatable. A problem of using strain gauges to measure stress is that the gauge must be correctly bonded to the surface under investigation otherwise inaccurate stress readings will be obtained. In the case of springs, there is difficulty in ensuring that the strain gauge is correctly bonded on the inside of the coils, thus limiting the use of small diameter springs. Bending of the gauge also produces inaccurate stress readings due to the strain induced in the gauge by the bend, and so the gauges cannot be used on highly curved surfaces. Thus there is a limitation on the size of the spring in that only large diameter wire springs with a large coil diameter can be used. The strain gauge must also be adequately protected from the environment as moisture and oil can reduce the sensitivity of the gauge, and this is achieved by coating the gauge with an impervious resin, normally the same type of epoxy resin which is used to bond the gauge to the test piece. The main limitation of the strain gauge method of stress analysis is that only the stress on the surface of the component is measured. Any stress concentration which may occur in the body of the component cannot be measured by this technique.

4. X-RAY DIFFRACTION METHOD OF STRESS MEASUREMENT

4.1. Theory of x-ray stress analysis

When a polycrystalline piece of metal is strained, the lattice plane spacings in the crystals change from their stress-free values to new values in proportion with the stress applied and the change in the appropriate elastic constants. The strain of the lattice causes relative shifts in the positions of the x-ray diffraction lines of the crystals from their stress-free positions, and these shifts are proportional to the change in the d-spacings of the crystals.

4.2. Experimental technique

X-ray diffraction stress analysis is carried out using standard x-ray equipment and testing techniques.

Tucker and Anderson(3) found that the selection of both the type of x-radiation and the atomic planes are of importance, to ensure that the resulting reflection has the maximum sensitivity to strain. While the specimen is stressed (or in a state of residual stress), two measurements of the d-spacings are made. One measurement is taken perpendicular to the surface and the other inclined to the surface at a known angle, lying in a fixed plane with the surface normal and the direction of the stress (Fig. 3)(4). The difference in the two values of the d-spacings indicates the difference between the two strains (ε_z and ε_ψ) and so it is possible to calculate the desired stress (σ). Using three measurements, two of which are inclined to the specimen surface, it is possible to determine two stresses at right angles to each other. All three exposures are produced on the same film to minimise errors due to film shrinkage in processing(5).

4.3. Limitations of x-ray diffraction technique

The economics of this technique are a major drawback. The x-ray diffraction equipment is exceedingly expensive to buy and a highly skilled operator is required to use it. Thus the purchase of the equipment can only be justified if it is going to be used often. Another limitation of the technique is that, as Barrett(6) found, only specimens which yield sharp diffraction lines give good accuracy with this method. Thus cold worked metals e.g. hard drawn wires, which yield diffuse lines which are difficult to measure accurately, do not yield consistent values for the stress.

The main limitation of x-ray diffraction stress analysis is that only surface stresses are measured. Thus any distribution of stress within a component is undeterminable by this technique. Also, the technique can only measure stress from a flat area of 1/8" diameter, thus there is a limit on the curvature of the component, and in the case of springs, small diameter wire springs and low index springs - both of which have a high curvature - cannot be analysed by this technique. Also, it is not practicably possible, with existing equipment, to measure the changes in the stresses in a component at elevated temperatures.

5. ULTRASONIC METHOD OF STRESS MEASUREMENT

5.1. Theory of method

As stress is applied to a solid, the elastic "constants" of the solid change. Ultrasonic shear wave velocities are dependent on the values of certain elastic constants, thus a change in the latter by application of stress results in a change in the velocity of the wave in the appropriate direction. This change is generally linear with stress.

Crecraft(7) used ultrasonics to measure stresses in axially loaded specimens (both in compression and in tension). Measurements were made of the variation with applied stress of the velocities of ultrasonic shear waves. These waves have a particle motion transverse to the wave propagation direction, and thus have a polarization analogous with polarized light waves. A shear wave propagated into a stressed (anisotropic) solid splits into two components polarized parallel to the effective stress axes in the plane normal to the wave propagation direction (Fig. 4). The difference between the velocities of the two components of the wave corresponds to the stress magnitude. The polarization axis of the wave (which is in the same direction as the propagation direction) is rotated to find the directions of the maximum and minimum wave component velocities, and hence the direction of the stress.

5.2. Experimental technique

The system normally used to measure residual stresses in materials, is the one developed by Forgacs(8) and consists of an ultrasonic pulse-echo system, capable of measuring velocity changes to 1ppm.

An ultrasonic pulse is propagated through the material using a y-cut shear wave transducer, the propagation direction being perpendicular to the stress axis. The times of travel over 1 in. (25.4 mm) of path length of the pulse are measured to 10^{-10} sec. Thus the difference between the polarized component velocities obtained corresponds to the stress in the test piece. It has been found that for an uniaxial tensile stress the time of travel over a fixed path length increases with stress, the reverse happening with uniaxial compressive stress. Thus not only the magnitude of the stress, but also the type can be determined.

5.3. Limitations and problems of ultrasonic testing

The propagation axis of the ultrasonic wave must be perpendicular to the stress axis of the component for an accurate reading to be obtained, so in the case of springs some prior knowledge of the stress pattern must be available so that the transducers are suitably sited. Thus there is a limitation in the coil diameter of the spring so that the transducer can fit inside the spring i.e. only large diameter coil springs can be tested.

Crecraft(7) and Smith(9) found that most metals have some degree of preferential grain alignment, and this results in a difference in the shear wave velocities even in an unstressed specimen. This effect can completely swamp the difference in velocities due to stress, and so a randomly orientated grain structure is required to produce accurate stress readings. This effect limits the use of hard drawn wire springs which always have preferential grain alignment. Although a great advantage of the ultrasonic technique of stress measurement is that it gives data about the stresses in the bulk of the component instead of just at its surface, its principal disadvantage is that it gives only the average stress value over the path length of the beam, and so the stress pattern in the bulk of the component is not obtained. Unfortunately, it is not practically possible to use this technique to measure stresses in components at elevated temperatures.

6. CALCULATION OF RESIDUAL STRESSES USING PHOTOELASTIC METHODS

6.1. Theory of method

Photoelastic methods of stress measurement involve the use of photoelastic resins. When a photoelastic resin is subjected to stress, changes in the optical properties of the resin take place which are proportional to the stresses developed in them. When polarized light is passed through the stressed resin, it splits into two separate beams, each vibrating along a principal stress axis and each travelling with a speed proportional to the magnitude of that stress. There is thus a "phase shift" between these two beams which produces a coloured interference fringe pattern if white light is used. Analysis of the polarized light will thus establish the plane of vibration of the beams and so the stress directions can be measured. The magnitude of the stresses are measured by interpretation of the colours in the interference pattern.

6.2. Experimental technique

An exact model of the component to be analysed is fabricated using a photoelastic resin either by casting the resin into a mould or machining the structure from a solid block of resin. The model is then placed in an oven and heated to its softening point, the appropriate scaled down forces are applied and are maintained while cooling the model to room temperature. The forces are then removed and the resulting stresses are "frozen into" the model. The model is then carefully cut into thin slices which are examined in polarized light and so the complete stress pattern within the component can be built up.

6.3. Limitations of photoelasticity

Although it is possible to produce springs from photoelastic resins either by casting or machining from a solid block (10), both are difficult operations. To cast a spring from a photoelastic resin requires the production of a complex mould which can be dismantled, and machining a spring from a block can only be carried out by a highly skilled operator. Since these are the only two ways of producing a photoelastic maodel of a spring, then stresses which are normally induced by spring making operations e.g. wire drawing, coiling, end grinding etc, cannot be measured. Only the stresses induced in springs by loading can be measured by this technique.

There is a second photoelastic method of stress measurement in which the model of the component is examined at room temperature while under stress, thus cutting out the "freezing" and slitting processes. However, this method can only be used for components which are relatively thin and which have the main stresses produced in the plane of the component e.g. stresses in the head of a spanner due to tightening a nut.

7. MEASUREMENT OF RESIDUAL STRESSES BY STRESS RELIEF

7.1. Theory of method

Stress relief methods of stress measurement involve the heating of a component in a state of residual stress to a fixed temperature for a fixed length of time to allow the dislocations within the component which cause the stress to move, thus reducing the stress. This removal of stress is accompanied by a change in the dimensions of the component which give an indication of the amount of stress relieved.

7.2. Experimental tecnhique

The dimensions of the spring are measured prior to heating. The spring is then heated in an oven to a fixed temperature for a specified length of time. After cooling to room temperature the dimensions are remeasured, thus giving an indication of the amount of stress removed. Stress relief of springs results in a reduction of the coil diameter and free length, and an increase in the number of coils.

7.3. Limitations of stress relief technique

Although this method of stress measurement can be used to give an indication of the amount of stress induced in a spring by each separate spring making process, it is a qualitative rather than a quantatative method, i.e. it gives an indication as to which process induces the largest amount of residual stress, but does not measure the actual amount of stress induced. This method only measures the average stress throughout the spring, it gives no indication to the actual stress pattern.

8. CONCLUSION

The literature survey has shown that of the methods available for stress analysis, only those methods discussed in this report are applicable for the measurement of residual stresses in springs. X-ray diffraction, ultrasonic and strain gauge methods can only be used for large diameter wire or bar. Strain gauges cannot be used at temperatures above ambient. X-ray diffraction and ultrasonic techniques could be used for examination of LTHT by heating the samples, cooling to room temperature and then testing them, providing the other difficulties of the techniques are overcome. Photoelastic methods cannot be used to measure the effect of LTHT as the stresses induced into springs by spring making processes, which are relieved by LTHT, cannot be induced into photoelastic resins.

9. REFERENCES

1. Hendry, A. W. Elements of Experimental Stress Analysis. Pergamon Press Limited. 1964.

2. Holister, G. S. Experimental Stress Analysis. Cambridge University Press. 1967.

3. Tucker, C. W. and Anderson, H. V. "X-ray Stress Analysis". Experimental Stress Analysis, 1952, 9, (2), pp. 67-74.

4. Kirk, D. "Theoretical Aspects of Residual Stress Measurement by X-ray Diffractometry". Strain 1970, 6, (2), pp. 75-80.

5. Norton, J. T. and Rosenthal, D. "Stress Measurement by X-ray Diffraction". Experimental Stress Analysis, 1944, 1, (2), pp. 73-76.

6. Barrett, C. S. "A Critical Review of Various Methods of Residual Stress Measurement". Experimental Stress Analysis, 1944, 2, (1), pp. 147-156.

7. Crecraft, D. I. "The Use of Ultrasonics in Stress Analysis". Strain, 1965, 1, (4), pp. 4-8.

8. Forgacs, R. L. Journal of the Acoustical Society of America, 1960, 32, (12), p. 1697.

9. Smith, R. T. "Stress induced in anisotropy in solids - the acousto elastic effect". Ultrasonics, 1963, (1), p. 135.

10. Stress Engineering Services Limited Private Communication. Sheffield.

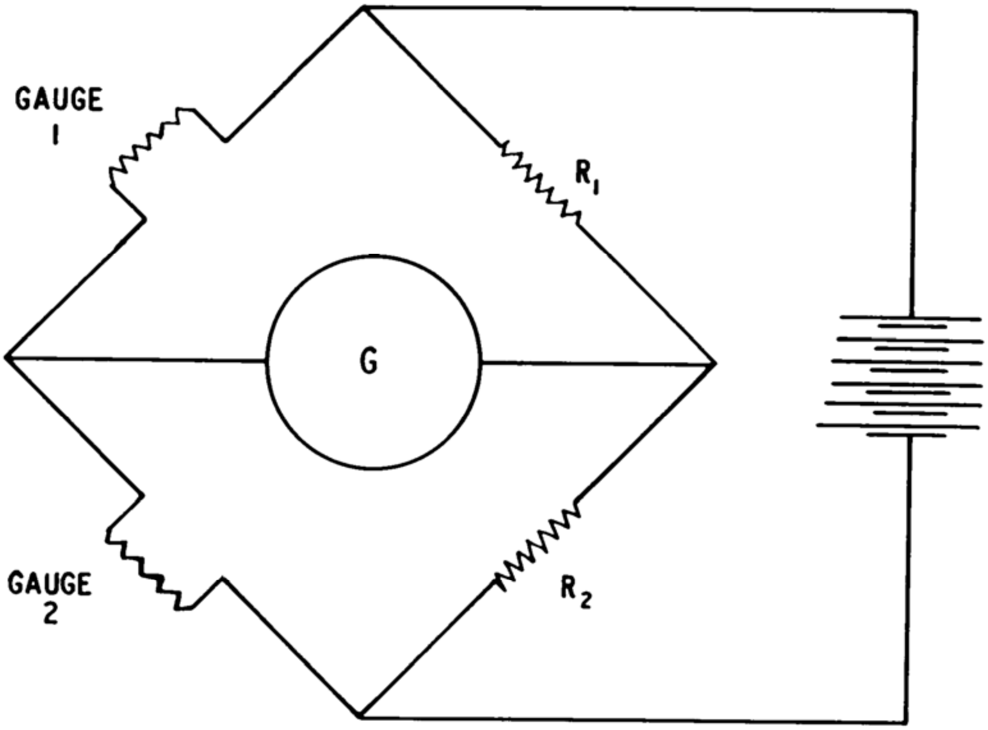

FIG. 1 SIMPLE STRAIN GAUGE CIRCUIT (1)

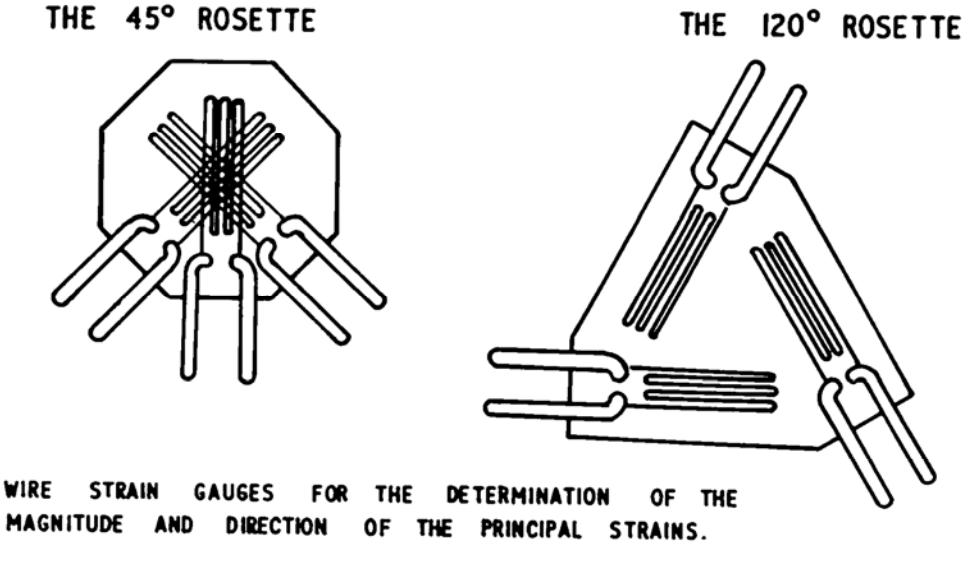

FIG. 2 VARIOUS ROSETTE STRAIN GAUGES (2)

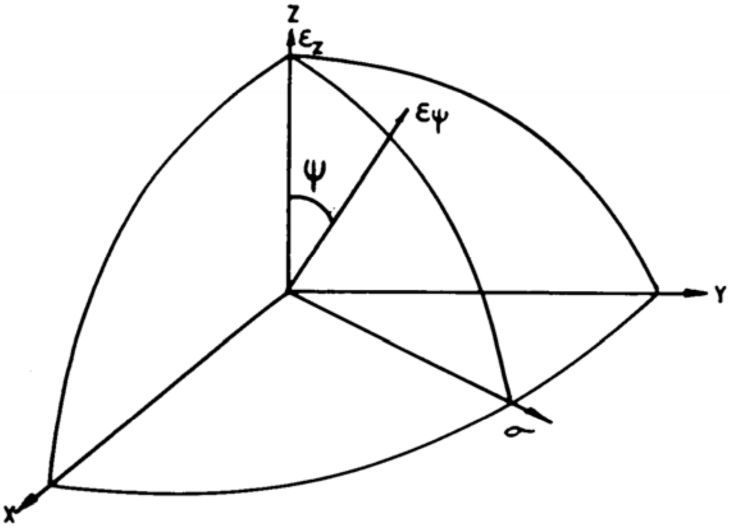

FIG. 3 COMPONENTS OF STRESS AND STRAIN USED IN X-RAY STRESS ANALYSIS (4)

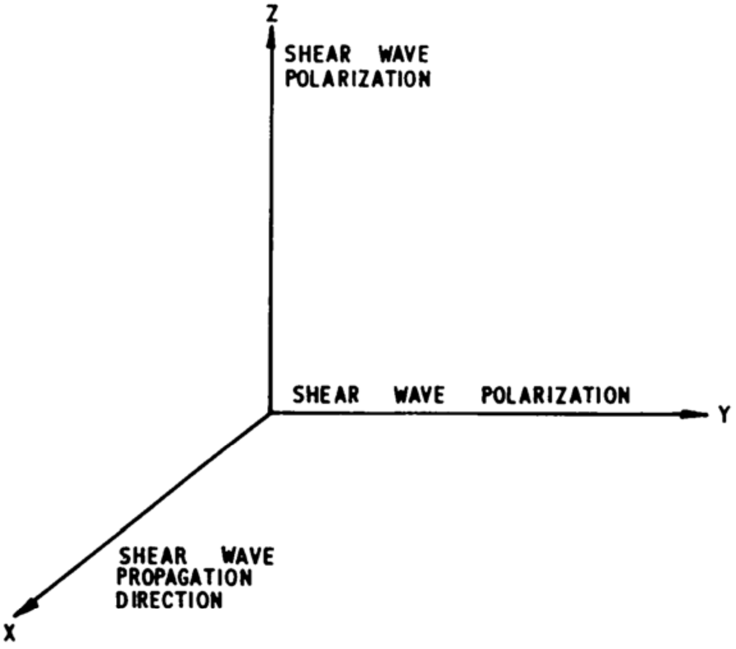

FIG. 4 CO-ORDINATE SYSTEM FOR SHEAR WAVE PROPAGATION IN STRESSED SOLIDS, STRESSES IN Y AND Z DIRECTIONS.