CoA NOTE 141

THE COLLEGE OF AERONAUTICS
CRANFIELD

THE DEVELOPMENT AND EVALUATION OF AN ULTRASONIC FATIGUE UNIT

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The Development and Evaluation of an Ultrasonic Fatigue Unit

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SUMMARY

A fatigue test apparatus operating at 20 kc/s is described. The unit is based on a standard magnetostrictive drive system as used in high energy stress-wave generators. An automatic counting device has been developed and incorporated in the final equipment, resulting in improvements in accuracy and reproducibility of results. Some typical results of tests on aluminium alloys are presented.

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1. Introduction

Of the many factors influencing the fatigue properties of metals, one presenting considerable experimental difficulties is the effect of test frequency. Interest in the effect of high frequencies is growing as a result both of engineering developments and the study of basic mechanisms of the fatigue process. In the field of engineering, many structures and components, particularly in high speed aircraft and missiles, are subjected to high frequency ($\sim 10^4$ c/s) cyclic stressing in service, and there is a requirement for property evaluation at these frequencies.

The existence of a frequency effect may make it difficult to extrapolate low frequency (conventionally 25 - 200 c/s) data to high frequencies but correlation of high and low frequency properties, and the shortened real time of test to 10^9 - 10^{10} cycles, are desirable features of high frequency tests. For these reasons there has been a recent revival in interest in methods for conducting fatigue tests at frequencies above 10 kc/s.

Early experiments, by Jenkin(1) and Jenkin and Lehmann(2), employed a beam specimen in flexure, driven at resonance by a pneumatic system. Frequencies up to 18 kc/s were obtained by this method. Later work(3), (4) used frequencies up to about 10 kc/s, produced by pneumatic, mechanical and electro-magnetic devices, but these were not readily adaptable for operation at still higher frequencies.

In order to realize alternating stress levels of sufficient magnitude for fatigue tests in the ultrasonic range, resonant systems using vibrators of the type used in high energy stress wave generators are an attractive possibility. Neppiras(5), (6) has discussed possible drive systems of this type and has developed a device employing a magnetostrictive nickel transducer and a velocity transformer, designed for operation at a fixed resonant frequency of 20 kc/s, in which the specimen is excited in a longitudinal tension-compression mode. Since these experiments showed that the method was capable of being employed for practical fatigue testing, an apparatus has been developed using a magnetostrictive drive system, as developed by Neppiras, to which has been added an electronic counting system. This report describes the essential design features of the complete apparatus and its preliminary evaluation.

2. Equipment

2.1. The vibrator system

A transducer and a velocity transformer as used by Neppiras(6) were adopted as the basis of the equipment and are shown in diagrammatic form in Fig. 1. This assembled equipment is illustrated in Fig. 2. The generator, described in a following section, feeds the magnetostrictive transducer which is coupled, by means of a screwed stud, to a double $\lambda/4$ velocity transformer with a velocity transformation ratio of 6.25 to 1. The transformer was machined from an aluminium alloy to specification L.65 (nominal composition Al - 4.4 Cu - 0.6 Mn - 0.7 Si - 0.6 Mg). The design of such transformers has been discussed in detail by Neppiras(7) and Balamuth(8) and will not be described here. The nodal support flange of the velocity transformer is fixed to a rigid plate which forms one end of a simple enclosure, allowing water cooling of the transducer.

A dumb-bell type specimen (Fig. 3) is attached to the velocity transformer by means of a screwed stud. It is essential that a good mating joint is obtained between the specimen and the velocity transformer, and between the transformer and the transducer. The screwed stud system has worked well and, as long as the mating surfaces are flat and clean, a smear of grease is all that is required to effect good coupling. The dimensions given in Fig. 3 are for aluminium alloy specimens. For other materials, longitudinal dimensions are changed by the ratio of the velocities of sound in aluminium and the material to be tested.

During a fatigue test, energy is dissipated in the specimen to an extent largely dependent on the internal friction properties of the test material. Since this is small ($Q^{-1} \sim 10^{-4}$) for the alloys tested, the temperature rise due to the energy dissipation would not be expected to be large. Direct measurements of temperature rise have been made by attaching a thermocouple to the specimen at the nodal point. At the highest stress level used, the temperature was found to rise by less than 1°C over a period of 300 seconds (6×10^6 cycles). The change in specimen length resulting from this temperature rise was less than 10^{-4} inches, which altered the resonant frequency by less than 10 c/s. This is outside the limit of accuracy of tuning and has a negligible effect on the amplitude. The change in modulus is also negligible, and the temperature rise has little effect on the fatigue properties of the material. The heating effect, therefore, is not significant in these experimental conditions with this material and it was considered unnecessary to cool the specimens during test.

A lead titanate-zirconate crystal is cemented to the free end of the transducer and provides a signal which is fed to the power generator. The system is maintained in resonance at a nominal frequency of 20 kc/s, the actual frequency of the system used being 20.4 kc/s.

2.2. The power generator and counting system

A block diagram of the apparatus in its final form is shown in Fig. 4. The developments leading to this are described below.

Fig. 5 shows the circuit of the ultrasonic power generator, which is based on a Mullard 60 watt generator, with the oscillator section removed. A phase shift network has been added between valves V_{1A} and V_{1B} and an amplitude limiting circuit included between valves V_{1B} and V_3. A stabilizing tube is incorporated in parallel with a resistor network, between H.T. positive and H.T. negative, to provide a stable D.C. bias for the amplitude limiting section. The degree of limiting can be adjusted by the potentiometer RV_1, which forms a section of the resistor network.

A lead titanate - zirconate crystal is mounted on the free end of the transducer and the output from the crystal is fed into the input valve of the generator. By adjusting the phase shift network, the system can be made to resonate at a frequency dependent on the geometry of the vibrator system, and at an amplitude dependent on the setting of RV_1. An accurate indication of both the stress in the specimen and the resonant frequency is given by the crystal output.

One of the major problems encountered in using the equipment was the accurate determination of the number of cycles to failure. During early experimental work, this was achieved by timing the period between the initiation of the experiment and the failure of the test specimen, the frequency being measured independently. The failure of the specimen was indicated by a fall in output from the crystal, when the system departed from resonance due to the formation of a crack. It is obvious that the errors involved in measuring frequency and time place a severe limitation on the accuracy of the system.

Since the high frequency voltage output from the crystal exhibits a sharp fall in amplitude when a macro-crack appears in the specimen, it can be used to trigger an automatic counting device. As the amplitude of this signal varies with the setting of the amplitude limiting potentiometer RV_1, an eight-way double-pole switch is ganged with the potentiometer and connected to eight pre-set attenuators. These are adjusted to give a constant signal at the grid of a single stage amplifier, irrespective of the stress level selected. The output from this amplifier is rectified and smoothed to give a D.C. level and then fed to the grid of the first stage of a Schmitt trigger circuit. When the crystal output rises to its maximum level (determined by the stress level), the trigger circuit changes state and the relay in the second stage is energised. When a macro-crack appears in the specimen, the crystal output falls and the trigger circuit reverts to its original state. By careful adjustment and selection of component values, the difference between the two trigger levels can be made very small, within approximately 2 - 3% of the maximum level.

The crystal output is also used to drive a dekatron counter via the relay in the Schmitt trigger circuit. This counter is of standard design, preceded by a voltage amplifier and a sine-wave shaping circuit which converts the sine-wave output from the crystal into pulses suitable to drive the four-digit counter. The counter is followed by a six-digit electromechanical counter, energised by the output pulse from the 10^4 dekatron, providing a total count capacity of 10^{10}. Fig. 6 shows the trigger and electromechanical counter input circuits.

The whole unit, consisting of power supplies, attenuator, trigger, counting and generator units, is contained in a three-rack cabinet, with internal forced air cooling to improve circuit stability (Fig. 7).

3. Stress calibration

The variation of strain along the specimen was determined by measuring the oscillatory amplitude at a number of points along its length. Measurements were made by focusing a travelling microscope, fitted with a mircometer eyepiece, on microscopic features on the specimen surface. When the specimen was driven, these marks showed an apparent increase in width, the width being twice the displacement amplitude. The slope at the nodal point of the curve of displacement amplitude, plotted against distance along the specimen, gave the maximum strain. This may be converted to stress by using a dynamic modulus of elasticity, which, for the aluminium alloys used, was taken as 10.7×10^6 lbs/in^2. Using the crystal output as a measure of the stress amplitude, a calibration is obtained relating crystal output to stress level.

In the later equipments, employing a counter circuit, the stress selector system was modified to give eight pre-set output levels. The calibration, carried out in a similar manner to that described above, results in a calculated stress level for each of the stress selector switch positions. Typical graphs of displacement amplitude, plotted against position along the specimen, are shown in Fig. 8.

4. Preliminary results

A number of preliminary tests have been carried out using the equipment described. Specimens were machined from extruded bars of L.65 (Al - 4.4 Cu - 0.6 Mn - 0.7 Si - 0.6 Mg nominal) and DTD.683 (Al - 0.4 Cu - 0.5 Mn - 2.7 Mg - 5.3 Zn nominal) and were heat treated as follows :-

L.65	Solution treated at 505°C for 2½ hours, water quenched and aged at 180°C for five hours.
DTD.683	Solution treated at 465°C for 2½ hours, water quenched and aged at 135°C for five hours.

From initial tests, it was clear that the surface finish of the specimens had a profound effect on the fatigue life, and therefore all specimens were electrolytically polished before test. This was accomplished in Lenoir's solution (817 cc orthophosphoric acid (s.g.1.57), 134 c.c. sulphuric acid, 156 gm chromic acid, 40 c.c. distilled water) maintained at 70-75°C, with a potential difference of 14 volts between the specimen and an aluminium cathode. The solution was stirred continuously during the polishing period of 9 minutes. 'Lacomit' lacquer was used to stop off the cylindrical ends of the specimen. After polishing, the specimens were chemically cleaned in a solution containing 350 c.c. orthophosphoric acid, 160 gm chromic acid and 650 c.c. distilled water, used at room temperature, in order to remove the surface oxide film formed during electropolishing.

Results of fatigue tests are presented in Figs. 9 and 10, in comparison with rotating bend test results obtained at a frequency of 200 c/s with similar materials. Although these latter results were not obtained using a direct tension-compression stress system, there is a pronounced frequency effect, the number of cycles to failure being considerably higher for the higher frequency tests. If there were no effect of frequency on the fatigue properties, the time to failure would be reduced by the ratio of the test frequencies only. The reported results show, however, that the time is reduced by a factor which is less than the frequency ratio. For example, for L.65 tested at $\pm$ 12 tons/in^2 maximum stress, at 200 c/s, the life is 2.2×10^5 cycles or 1100 seconds, while at 20 kc/s the life is 10^7 cycles or 500 seconds.

In these preliminary tests, the scatter in results did not appear to be significantly different to that experienced in low frequency tests.

5. Discussion

A high frequency fatigue testing apparatus, operating at 20.4 kc/s, has been developed and no major difficulties have been encountered in its operation. The provision of an automatic counting facility is a desirable feature and is of particular importance at high stress levels, where the specimen life may be a few seconds only. Neppiras(5) has estimated a probable error of ± 10^5 cycles (± 5 secs.) in determining the life to failure, using stop-watch timing. Although the counter system itself is accurate to ± 1 cycle, an error in life may arise dependent on the setting of the amplitude gate. In practice, this error has not exceeded a few thousand cycles, and therefore a considerable improvement in both accuracy and reproducibility has been achieved, particularly for high stress, short life tests.

For calibration of stress levels, it is necessary to use inherent surface markings as datum points for the measurement of displacement amplitude. Artificially produced markings cause such a large notch effect that the life of the specimen becomes too short for satisfactory measurements to be obtained.

The electrolytically polished and chemically cleaned surface, adopted as standard during these tests, was found to be satisfactory. Work to investigate the effect of surface finish on the high frequency fatigue properties of these materials is in progress and will be reported later.

The results suggest that a real frequency effect exists. At low test frequencies the fatigue properties of the precipitation-hardening alloys tested show only a slight dependence on metallurgical condition(9). Since the metallurgical processes which may occur in these alloys are time dependent, and as it is known that cyclic straining can modify precipitation processes(10), it might be expected that the rate of cyclic straining would be significant and that the initial metallurgical condition might be more important in high frequency testing. Further work on this aspect is in progress.

Since no simple correlation between high and low frequency test results has been established as yet, the method is not suitable, at the present time, for accelerated evaluation of fatigue properties. The technique has applications for teaching purposes, as many of the features of the fatigue process may be demonstrated in a short time.

6. Conclusions

1. A practical high frequency fatigue testing apparatus, operating at 20.4 kc/s, has been constructed. The transducer unit is of the type developed by Neppiras(6). A pre-set stress selector system and an electronic counting device has been incorporated in order to improve the accuracy and the reproducibility of the results.

2. The results of fatigue tests on the aluminium alloys used are highly sensitive to the surface condition of the specimen.

3. A pronounced frequency effect has been observed. The application of the equipment to accelerated evaluation tests may not be simple.

4. Further work should be directed towards an investigation of the effects of surface condition and metallurgical variables on the fatigue properties.

7. Acknowledgements

The authors wish to thank Mr. E. A. Neppiras of Mullard Equipment Ltd. for advice and help during the development of the equipment.

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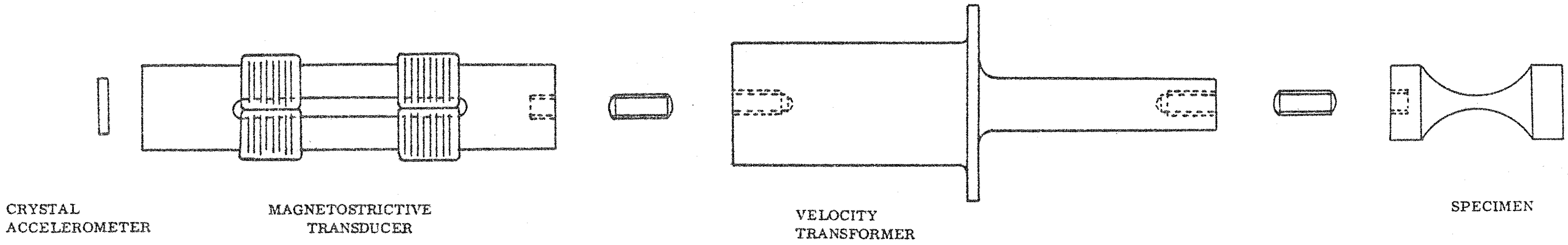

FIG. 1. DIAGRAM OF VIBRATOR SYSTEM

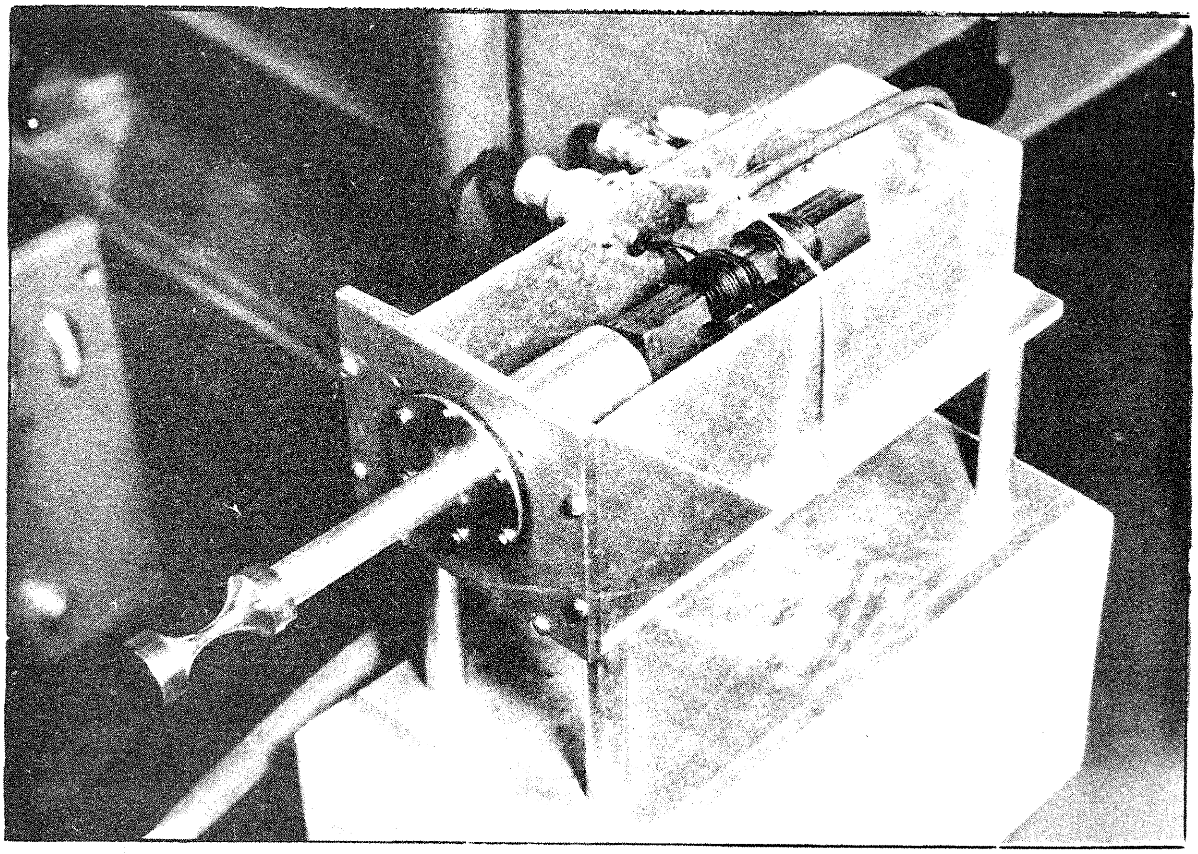

FIG. 2. ASSEMBLED VIBRATOR SYSTEM

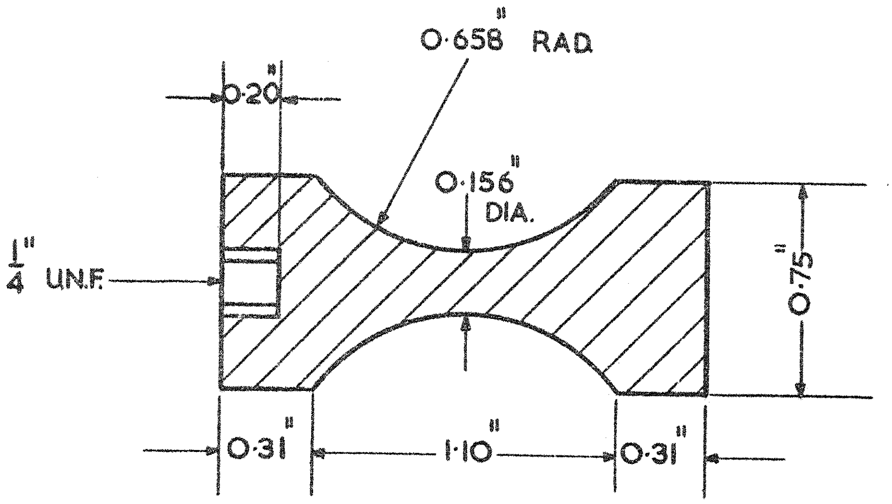

FIG. 3. ALUMINIUM ALLOY SPECIMEN

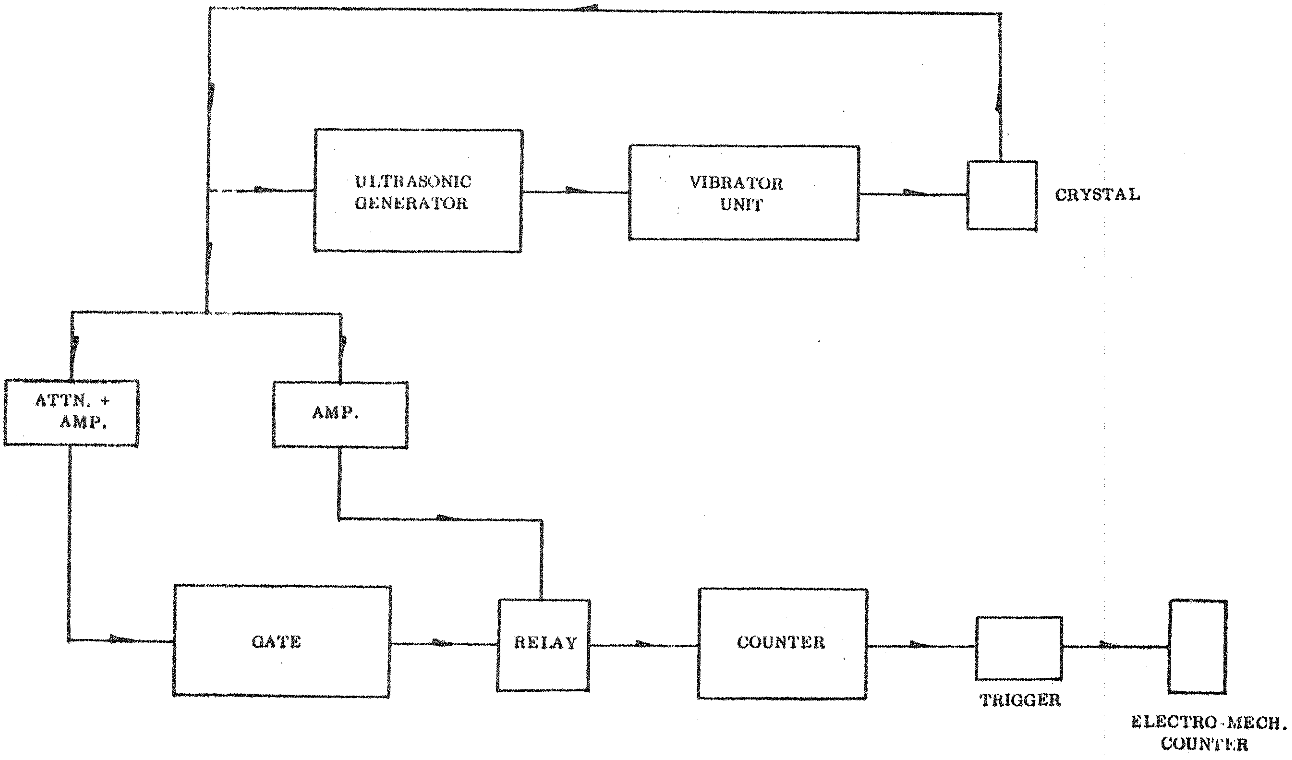

FIG. 4. BLOCK DIAGRAM OF GENERATOR AND COUNTER SYSTEM

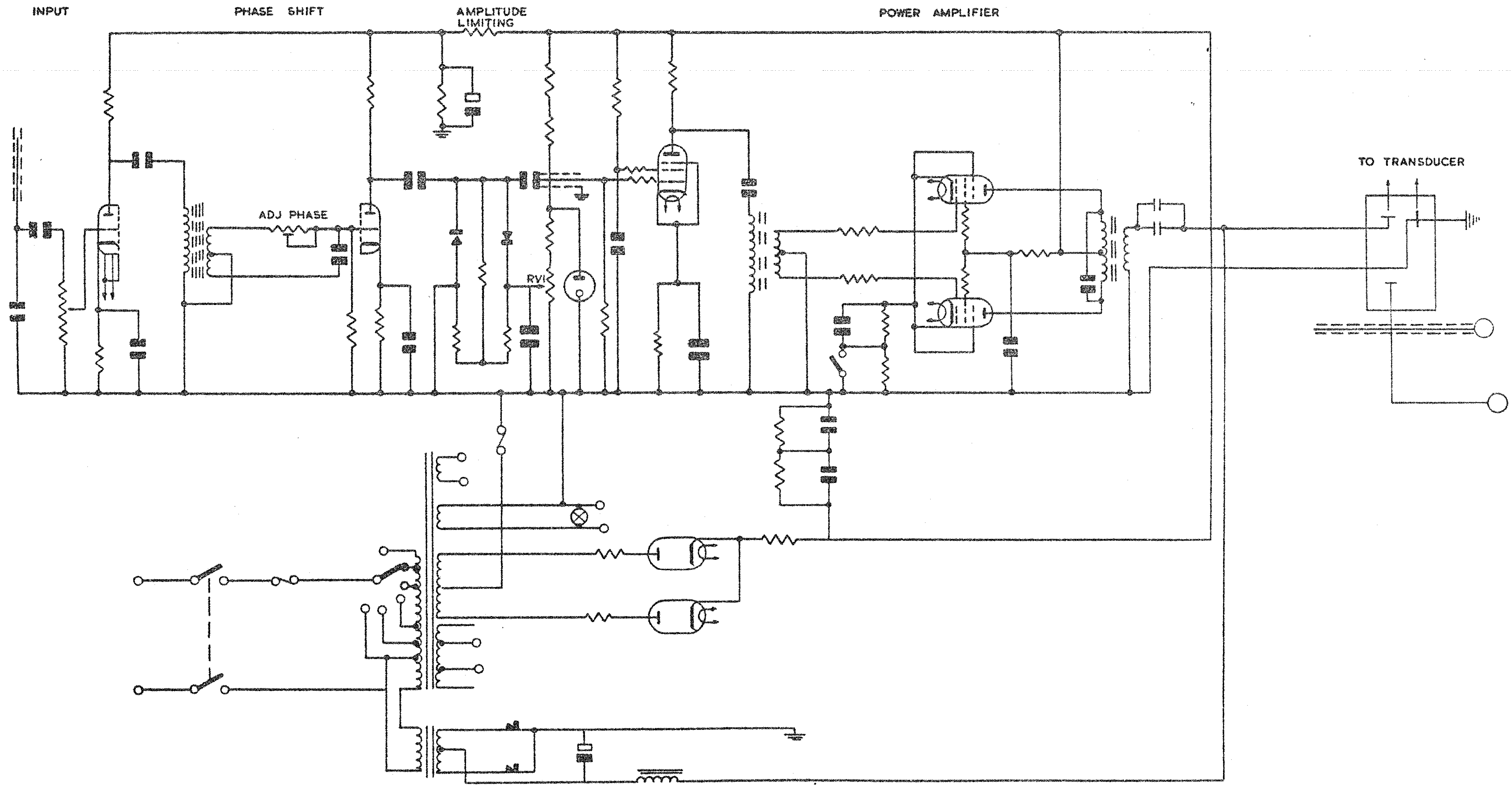

FIG. 5. CIRCUIT OF MODIFIED MULLARD GENERATOR

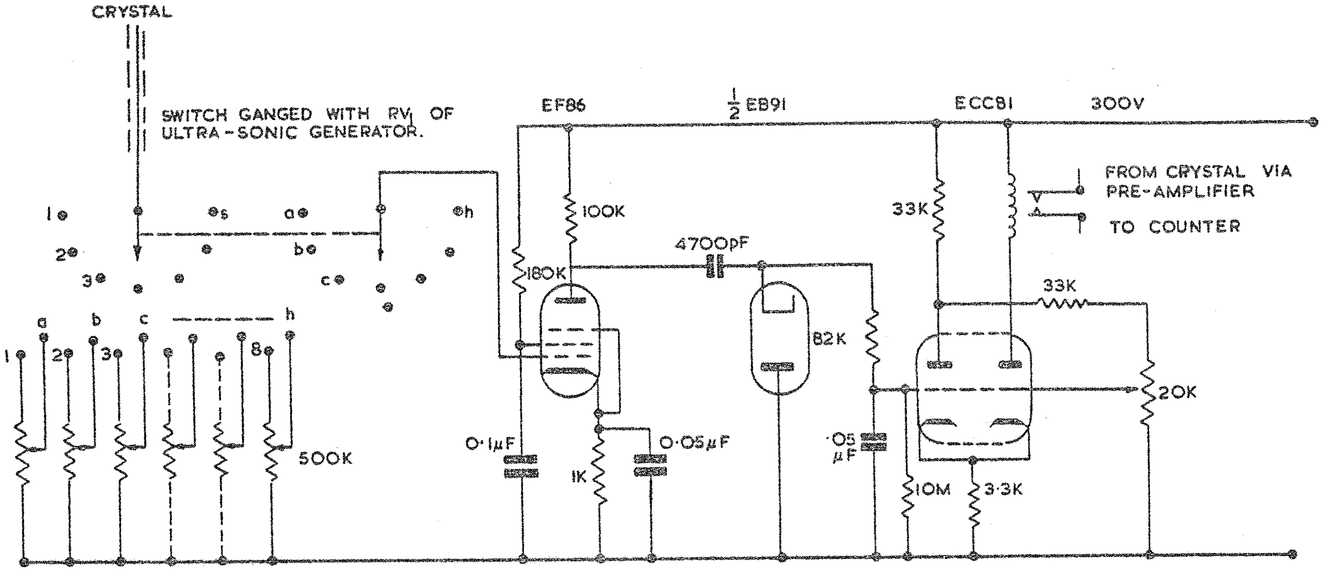

FIG. 6 (a) GATE CIRCUIT

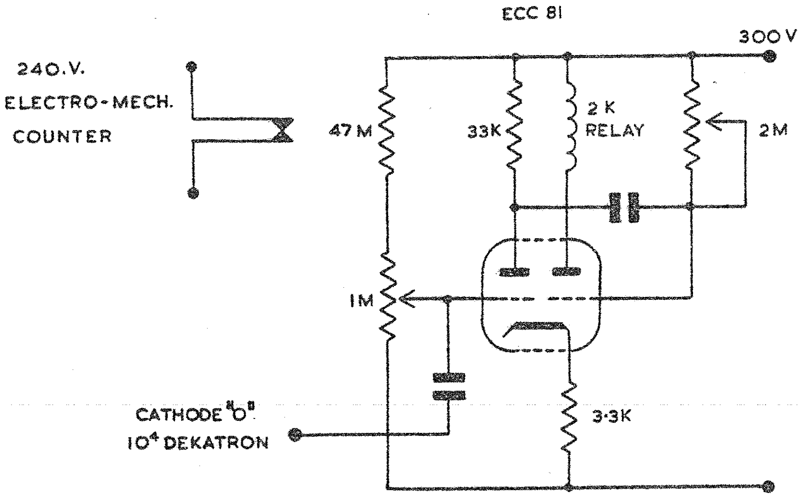

FIG. 6 (b) ELECTROMAGNETIC TRIGGER CIRCUIT

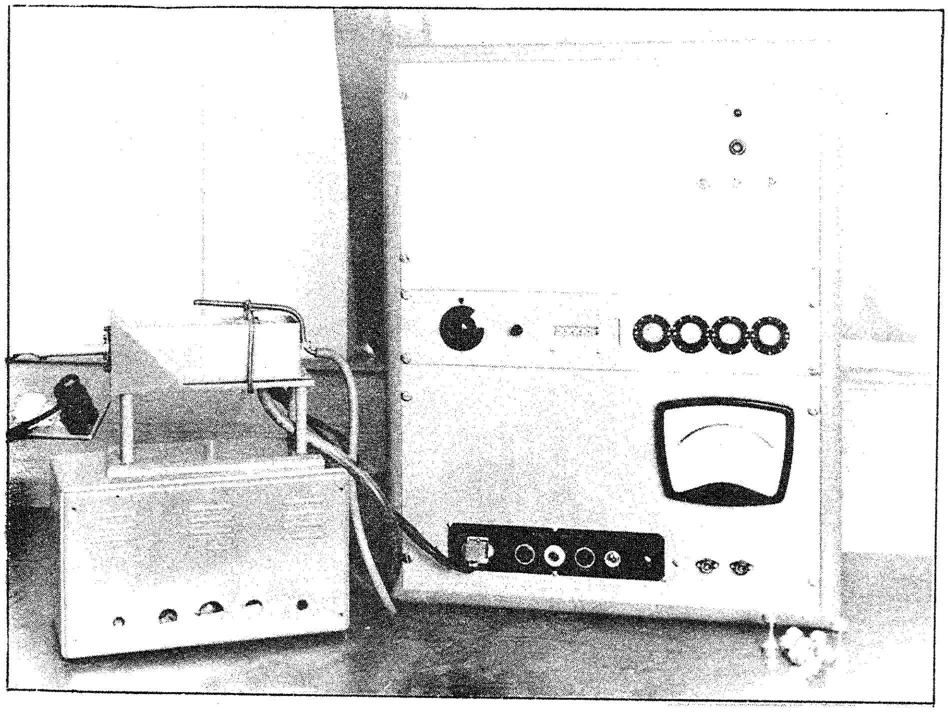

FIG. 7. ASSEMBLED FATIGUE UNIT

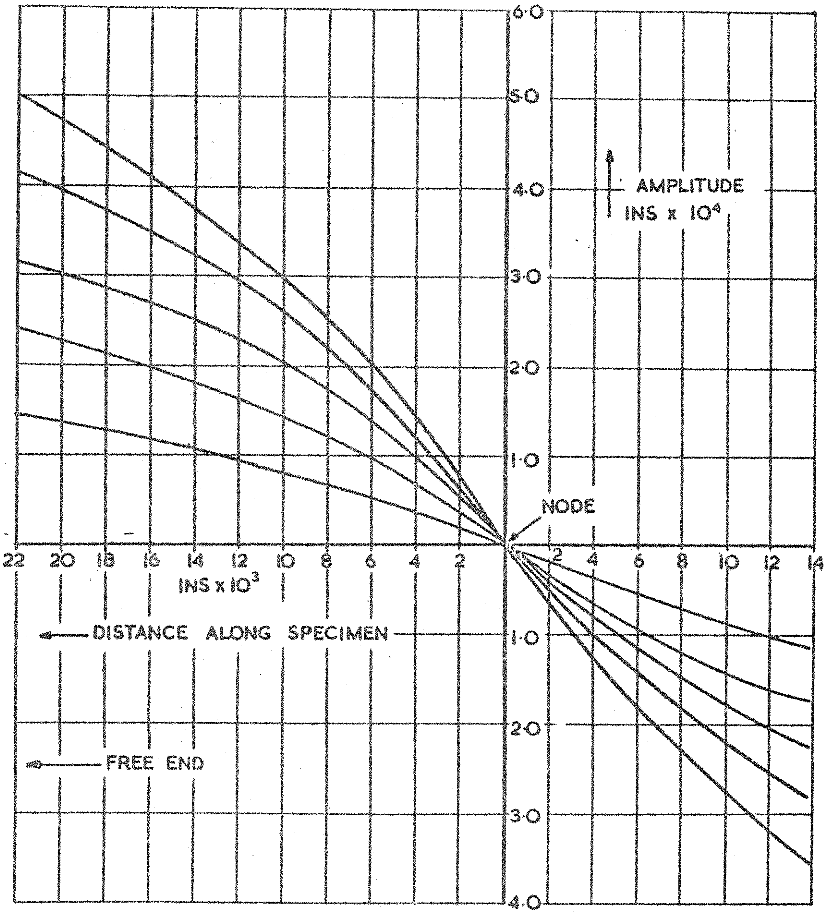

FIG. 8. RELATION BETWEEN OSCILLATORY AMPLITUDE AND DISTANCE ALONG SPECIMEN FOR SEVERAL STRESS LEVELS

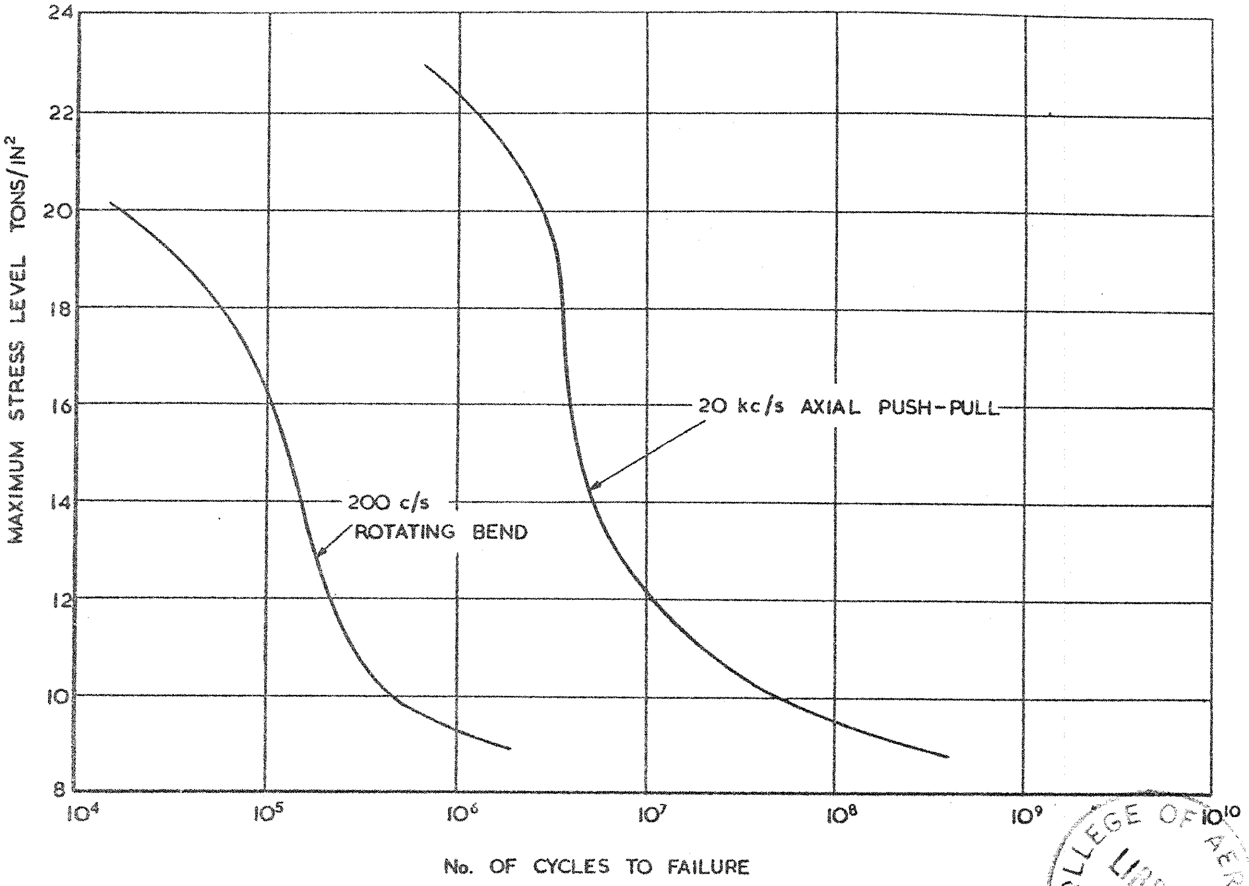

FIG. 9. COMPARATIVE FATIGUE DATA FOR L. 65

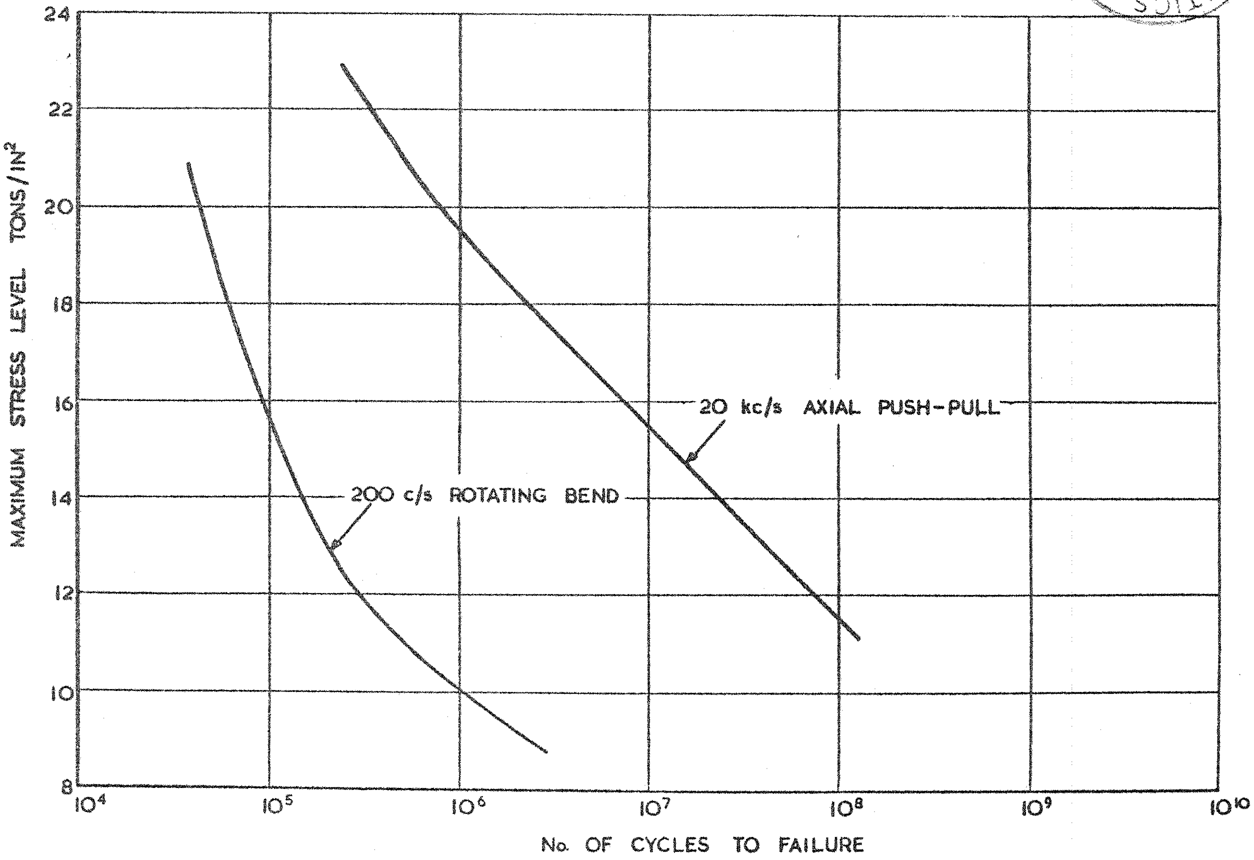

FIG. 10. COMPARATIVE FATIGUE DATA FOR DTD. 683