ULTRASONIC DEFECT DETECTION IN SOLID SHAFTS AND ELECTRONIC LOAD MEASUREMENTS

By J. R. GUNN.

To say that there is nothing new under the sun is an adage which is usually very accurate when one analyses most modern inventions. I will attempt to deal with two very recent acquisitions in the field of engineering science and as we progress you will see that although the equipment is highly complicated, it is basically only doing what has been done for many centuries, but of course, in a far more accurate manner.

THE ULTRASONIC DEFECT DETECTOR

The usual method of testing certain metals for defects is to give whatever is to be tested a sharp blow or tap with a hammer and listen to the ring or sound emitted. This is done by the carriage and wagon examiner who taps wheels on the railways, by fitters working on locomotives who deliver a mighty blow with a four pound hammer on the crankpins of the driving wheels to endeavour to establish whether (*a*) the pins are loose or (*b*) whether they are flawed. These audible sounds vary in frequency from 16 cycles or vibrations per second to 16,000 cycles per second, the higher the note the higher the frequency. It is safe to say that in most cases the defect is revealed by a dull note instead of a sharp note, and that this note is usually of lower frequency than that emitted by a "sound" unflawed specimen. It is a known fact that every object when struck by another object will tend to set up vibrations of a frequency peculiar to that specific object, dependant on the nature of material of the object and on its shape and size. If the vibrations are audible the frequency must fall between 16 and 16,000 cycles per second. If the object is defective, the structure of the material will be different from the original, and this will cause a different frequency, usually lower, and the tester will report that he has discovered a defect, and, in nine cases out of ten, the object will be discarded without knowing what, where or to what extent the defect exists. In some cases this may be very wasteful and uneconomical.

With the advancement of science some more accurate method of testing of expensive machinery was evolved to meet the requirements of safety and economy. There are such testing apparatus as X-ray, magnetic crack detector and ultrasonic testing. The latter device is basically the same as the wheel tapping method except that the frequency of vibrations set up in the shaft are far beyond the audible range.

The apparatus consists of an electronic impulse generator which can be tuned to predetermined frequencies of $\frac{1}{2}$ megacycles per second (or 500,000 cycles per second) to $2\frac{1}{4}$ megacycles per second (2,250,000 cycles per second). Impulses at the above frequency are fed to a tuned quartz crystal, which is held in contact with a smooth surface on the material to be tested. These impulses are transmitted to the object for a specified time interval and then cut off. In one manufacturer's apparatus this space of time is $\frac{1}{4}$ microseconds or 1/400,000th of a second. Echoes reflected back from various parts of the material to be tested strike the quartz crystal, re-energise it and another section of the electronic apparatus picks up and correlates the echo impulses with the original signal impulse. In order that the results may be visually interpreted the information is fed to an oscillograph or cathode ray tube. This is effected in the following manner.

The thyratons which cut off the high frequency impulses to the quartz crystals also influence a visual horizontal line on the oscillograph screen, so that instead of it being a straight line it is in the form shown in Figure 1.

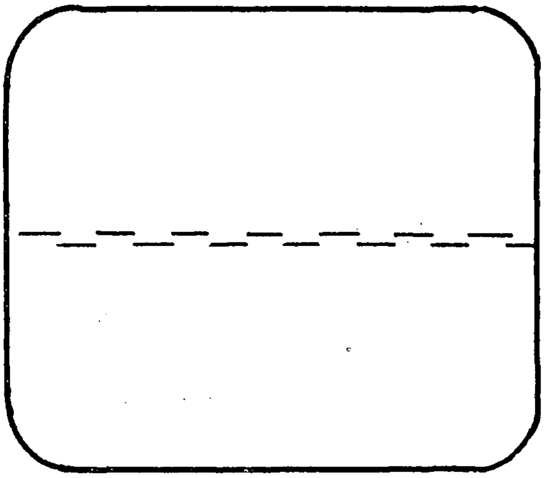

FIG. 1.

Each dash in the line represents a definite interval of time. As the ultrasonic impulses travel with a definite speed through the material, then, as we travel from left to right across the screen or "time lines" and multiply the time represented by the dashes by the speed of transmission of the vibrations, we can establish a specific distance. To quote a more easily conceivable case, if a car travels for 2 hours at 30 miles per hour, the distance travelled will be 2 × 30 or 60 miles. In the case of the ultrasonic tests if the time interval is 1/400,000 second and the speed of transmission is 4000 feet per second and one dash on the screen represented each thyraton cut off, then one dash would represent 1/400,000 × 4,000 or 1/100th 'of a foot or approximately 1/8th of an inch, that is, one dash would represent 1/8th of an inch. In actual fact the apparatus is arranged so that each dash can be tuned ro represent either 1 inch or 1 foot, depending on the size of specimen to be tested. By this means we have a means of establishing a distance by merely counting the number of dashes.

The reflected echoes will take a certain amount of time to return to the generating crystal, and as the transmission speed is constant, the time taken will depend on the distance from which the echo has emanated. The received echo signal is detected, amplified and fed to the vertical deflection plates of the cathode ray tube, which causes the visual image to make a vertical line as illustrated in Figure 2.

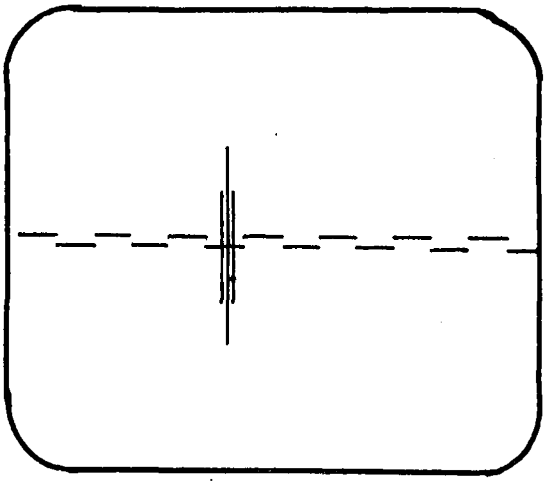

FIG. 2.

Figure 2, being interpreted, would mean an echo being received from a point 2′ 9″ from the end of the object being tested. In actual practice the ultrasonic vibrator head receives an echo from the contact surface with the specimen being tested, and therefore the actual picture is shown in Fig. 3, having an echo at zero distance and an echo at 2′ 9″'

Testing Procedure with Ultrasonic Equipment

The only essential preparation of a test piece is to remove old paint and rust in order that the crystal sound generator may make intimate contact with the shaft. To quote a case as far as sugar mills are concerned, if it is desired to examine mill roll shafts with the ultrasonic tester, all that is necessary is to remove the sprockets, if any, from the pintle end and the coupling box and bar from the drive end, and to clean the end surfaces carefully.

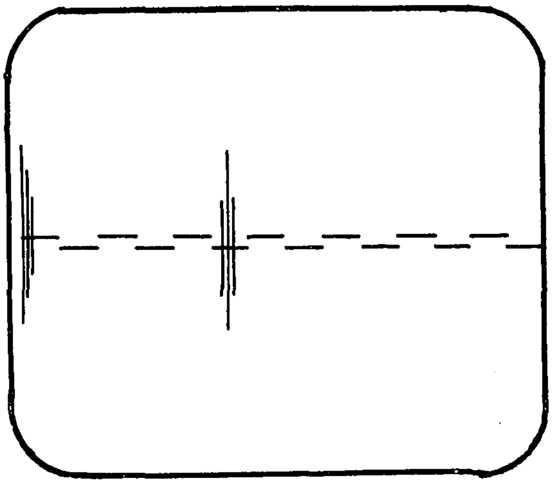

FIG. 3.

In order to ensure the required intimate contact between the sound generator and the shaft, the surface of the end of the shaft is sprayed with oil to exclude air. Depending on the length of the shaft and the nature of the material, a sound generator of the required frequency is selected and the apparatus circuits are tuned to suit the testing head. The head is applied to the shaft and the readings are then interpreted. One essential piece of information is required for the correct interpretation of the oscillograph chart, and that is the physical geometry of the shaft. Therefore the operator must know where there are fillets, shoulders, keyways, etc. In order to test a shaft properly it must be tested from both ends, so that the influence of shoulders, changes in section, etc., will be cancelled out. Reference to figure 4 shows the ultrasonic sound generator on the square driving end of a mill roll shaft.

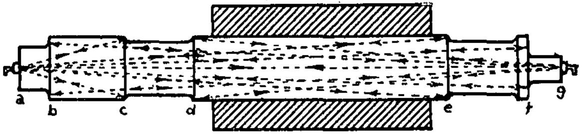

FIG. 4.

You will notice that I have tried to depict rays being emitted, striking reflecting surfaces and returning to the testing head. Assuming that there is no defect in the shaft, the oscillograph figure will be as shown in figure 5. The vertical deflections of the distance line will be caused by echoes from the changes in section of the shaft.

Testing from the other side (or pintle end) will give a result depicted in figure 6.

Now, first of all there is one feature to noticc, namely the oscillograph always records from left to right, and even though in figure 4 the pintle end is

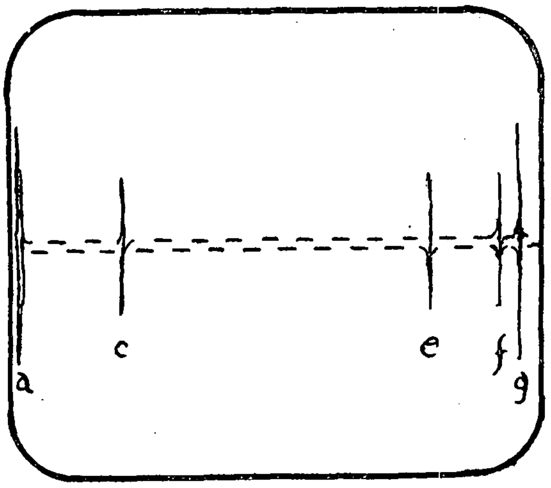

FIG. 5.

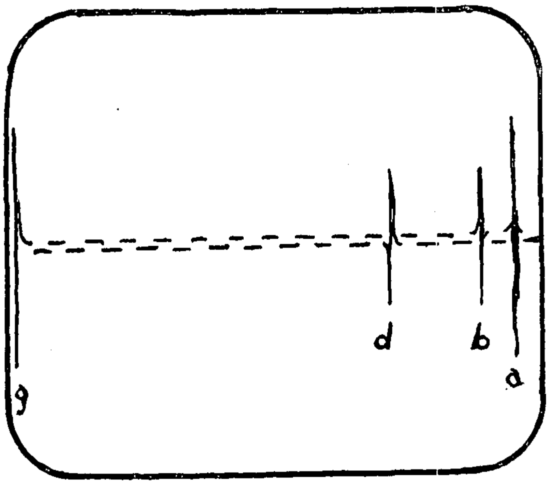

FIG. 6.

on the right and testing from that end the sound will travel from right to left, it is nevertheless recorded from left to right as the instument is only interested in the time between the emitted sound, and the echo, and not in the direction it travels. It is to be noticed that certain fillets and changes in section are picked up in one direction and not in the other. This is due to there being no reflecting surfaces in one direction, for instance, from the pintle end the rays will pass through the outside end of the bearing journal, and as these do not leave the shaft, they will not meet any reflecting surface. It is for this reason that the geometry of the shaft must be known. Assuming there is a crack in the shaft under the shell as shown in figure 7, the sound rays will be reflected from the crack as well as the fillets, etc., and a vertical deflection will reveal itself on the dial at a point where the geometry of the shaft tells the operator that there should be no echo. Whereas testing from the other side of the shaft does not reveal the same changes in geometry, a crack will show up at the same spot in the shaft, but obviously when tested from the other side the distance will be read off on the dial at a point of L — A from the end.

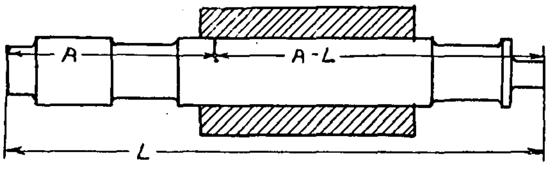

FIG. 7

Having located a crack we must now investigate it to ascertain whether the shaft must be condemned or not. This is done with an angle beam which emits beamed sound at 45° to surface of the testing head. Reference to figure 8 showing an enlarged portion of the shaft shows how the angle beam is used.

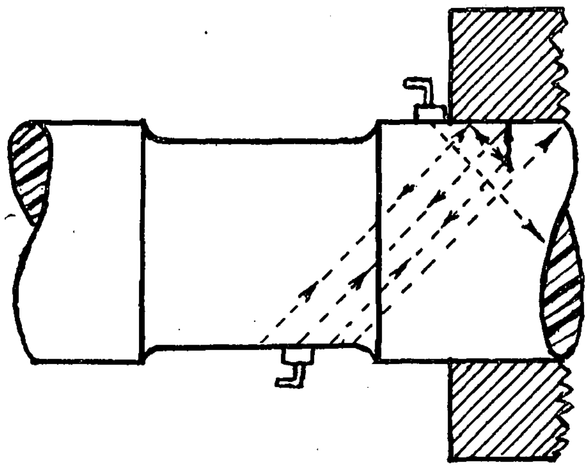

FIG. 8.

With the angle beam, if no fillet is encountered and no crack is present, no echo is obtained. If there is a crack in the shaft and its position is located with the direct longtitudinal beam, then by sighting the angle beam to hit the crack a reflected echo will be received at the transmitting head. By moving the angle beam longitudinally backwards and forwards on the shaft a distance on the shaft can be marked off where echoes are received. By moving the head radially at the same distances as those marked, the crack can be traced round the shaft. By suitably interpreting the area on the shaft on which echoes are received, the depth and radial length of the crack can be calculated by simple trigonometrical or geometrical methods. If the crack is under the shell, a direct reflection may not be obtained due to the shell interfering with the testing head as shown in figure 8, but this does not prevent testing from being carried out on the other side of the shaft as indicated.

I have omitted to state that any ultrasonic waves leaving the skin of the object being tested do not effect the dial indications at all. Thus any sound waves leaving the steel shaft and entering the cast iron shell do not return, and therefore the cast iron shell does not influence the testing in any manner at all except that it gets in the way if a crack is found.

Anything welded to the shaft will influence the results very materially, since welding is the actual fusing of one object to another, so that ultrasonically the two objects are the same mass of material and reflections will be picked up from the welding fillets. In this instance, it is interesting to state that one shaft at Tongaat came under suspicion of being cracked, until the operator of the ultrasonic tester located the crack on his screen, measured back on the shaft and found a juice guard tacked to the shaft by welding. So accurate was his machine that by running the testing head radially round the end of the shaft he told me, by interpreting the readings on the screen, how many tacks there were on the juice guard and exactly where they were radially round the shaft circumference.

Benefits derived from Ultrasonic Testing

The benefit of being able to test anything without destroying it, as in a tensile test, is obvious. It is a source of great satisfaction to me to know that, having had all the shafts of two tandems ultrasonic tested, I have 50 mill roll shafts free of flaws and cracks. Had this testing been done during 1953 it may have avoided the inconvenience and expense of having two roller shafts fractured in operation. We have found by bitter experience that the crankpins of slow speed horizontal mill engines are prone to failure, and all these were tested. I believe that at Illovo Sugar Estate, when testing axles of the railway trucks, approximately 10 per cent. were found to have been cracked just inside the wheel bosses.

During my period of service in the South African Railways at Cape Town the Class 23 locomotives began to suffer from severe breakages of driving and coupled wheel axles as well as side rods. This became so chronic that special instructions were issued that the "life" of axles on that particular class of locomotive was to be reduced. This meant that when a certain period had elapsed the axles were to be discarded irrespective of their condition. This was a very costly business. Now the problem has been solved by ultrasonic testing, and good axles are given a further lease of life, thereby keeping the locomotives in service longer and saving the expense of a "wheel change" which involves 10 days solid work.

To quote a case of saving at Tongaat, we discovered that an imported shaft which has had four reshells gave the clearest screening of all 50 shafts and was declared the best shaft at the mill. It had been put aside as a risky shaft due to its age, but now is a certainty to be reshelled for the fifth time. Another shaft from the 84″ tandem was discovered to have been cracked when it was being dressed up for a reshell at an engineering firm in Durban. The crack was machined with a round nosed tool and it persisted down to about ½″ depth, so the shaft was abandoned. During the ultrasonic testing, the depth of the crack was measured with an angle beam, and was found to be only another ½″ deeper. As the journal size of the shaft is less and the shell seat by much more than the depth of the crack, it is proposed to turn out the crack and have the shaft reshelled. In itself that represents a saving of approximately £600.

While ultrasonic testing is a comparatively simple operation, it requires skilled operation and interpretation of the dial readings. It is not considered that a set purchased by, say, the Sugar Milling Research Institute or an individual sugar company would be an economical purchase as the equipment is costly. On the other hand, provided sufficient companies can agree to having rolls tested at certain times so that the operator can travel from one mill to the other, the cost of having the services of the South African Bureau of Standards is very reasonable.

Electronic Load or Strain Measurements

To go back in time again we find in heavy engineering and also in comparatively modern aero-engineering, that in many instances the loads applied to various parts of machinery were gauged by the extension or lengthening of premeasured bolts and cotter pins. To quote two examples, in locomotive fitting procedure, in order to ensure that the piston rod is tight in the cross head, the cotter pin is driven in lightly and then marked, it is then driven in a further ¼″ on the taper, this compressing the taper pin and loading the piston rod so that it is rammed tightly into the crosshead. In aero-engineering the bolt clamping the one web of a Bristol radial engine is coupled up and its length is measured with a micrometer. It is then tightened up until it had stretched .060 inches, and the fitter is then assured that the crank web is tightened up to the required amount, or in other words, that the bolts have been sufficeintly loaded.

It is common knowledge that when any material is stretched or compressed the cross section area of the body either becomes less or more as the case may be. This change in area follows a direct relationship to the tension or compression in the body and is a function of Poissons Ratio. Working on the theory that an increase in tensile loading will cause increase in length of a body with corresponding reduction in area, the electronic engineers have evolved a method of analysing strains by making use of the physical properties of cross section area changes coupled with its effect on electrical resistance. Assume we have an accurately rolled piece of resistance wire of known Young's Modulus and Poisson's Ratio, if we stretch the wire there will be the attendant reduction in cross sectional area. The electrical resistance of the wire will depend on the length of it and on its cross section area. If it is stretched, the length is increased and the area is reduced, the latter increasing the electrical resistance and the former further increasing it as the wire is now longer. If the wire is arranged as shown in figure 9 the effect of stretching the wire is further increased.

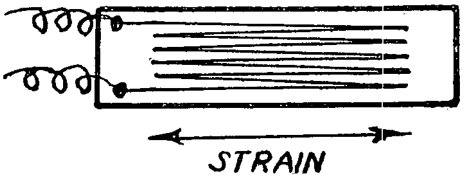

FIG. 9.

The amount of change of resistance is microscopic but that does not bother the electronic expert because he uses thermionic amplifier valves to magnify the results into measurable quantities.

Next feature employed in load or strain analysis is the standard Wheatstone Bridge, which is known to anyone who has studied basic physics or electrical science. Figure 10 shows the circuit employed.

An alternating current of 110V. at 400 cycles per second is fed to the two ends of the bridge system which comprises in a very simple form of two adjustable resistance R_1 and R_2. These are made adjustable to enable various ranges of testing to be performed and S_t and S_f, which are the strain gauge which does the testing, and the strain gauge element which is not subjected to any strain but is used in a fixed capacity to balance the zero position of the instrument. The connection between R_1 and R_2 and between S_t and S_f are connected to the electronic amplifier for magnification and interpretation.

If the resistance values of $\frac{R_1}{R_2} = \frac{S_t}{S_f}$, then there will be no current flowing through the bridge and the bridge will be in balance. To put it in another form $S_t = \frac{R_1}{R_2} \times S_f$ and as R_1, R_2 and S_f are fixed, once the instrument has been zeroed, then any change in S_t will cause the equation to be upset and therefore current will flow to the electronic amplifier.

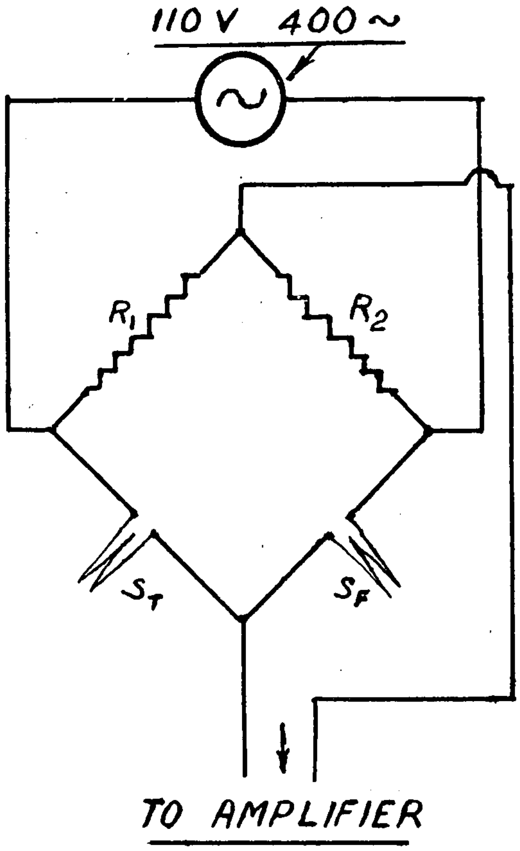

FIG. 10.

Method of testing for Strains and Loading

By preliminary calculations or by knowledge of the approximate loading, the correct ratio of R_1, R_2, S_t and S_f is selected. The strain gauge S_t, which is a small plastic instrument about 2″ long × ½″ wide, is fixed to the object to be tested by means of a cullulose adhesive at each end of it, so that if the object stretches the strain gauge will stretch with it. In order that temperature will not affect the accuracy of the test, strain gauge S_f is fixed adjacent to S_t, but on this occasion S_f is only glued at one end so that any stretching of the test piece will not effect S_f. The electrical wiring is completed and the instument is brought to zero by adjusting rheostats and potentiometers to counteract for length of leads, etc.

When the load is applied to the test piece it will either be compressed or lengthened a microscopic amount, and the information passed to the amplifier will be detected, amplified and reflected on a dial for a static type of tester, or reproduced in a form of a graph on sensatised paper for a dynamic tester which will record a continuous strain analysis of a sequence of events, such as the Strains taking place in a piston rod or connecting rod of an engine.

From the reading of the static dial type or the chart of the dynamic tester, we can evaluate the actual strain or elongation or compression which the strain gauge has suffered. It is necessary to know the Young's Modulus of the material of the test piece in order to calculate the actual stress. This is done by multiplying the strain gauge factor by the Young's Modulus. To obtain the actual loading the stress has to be multiplied by the cross section area of the test piece.

I have referred to "test piece" mainly for want of a better word. The test piece is actual machinery in motion an not a laboratory test piece. Let us now consider where we can use this equipment in a sugar mill and factory. For the practical engineer, there is not very much use for it as the correct results require quite involved mathematics to be used and as the engineer has to do the best with the machinery he has and knowing the stresses set up in individual components do not make much difference to its operation. However, the designer or manufacturer of the machinery could derive great benefit from its use.

Take for example, the case of mill headstocks alone. We have a firm in Glasgow supplying mills with hydraulic rams the same size on the gearing side and on the pintle side, and the same supplier furnishing other seemingly identical mills with larger rams on the gearing side to balance the climbing effect of the mill pinions thrusting away from each other. By using strain gauges on the vertical cheeks of the top roller bearing guides on both sides of the mill, the difference in loading on each side headstock can be evaluated. There is another firm of mill suppliers which has the cap inclined at an angle. In order to establish whether the angle is correct, strain gauges placed at varying angles on the headstock near the top, will establish which angle gives the maximum reading and therefore at which angle the cap should be inclined. The loading on mill rollers and the effects of mill settings can be established by measuring the compression of the actual mill roller bearings. Most text books on mill extraction seem to be indifferent regarding the setting of the trash plates, but a strain gauge analysis of the loading taken by the trashplate could easily be obtained by fixing strain gauges to the dumb turner and to the dumb turner draw bolts. For the designer or research engineer, invaluable information can be obtained by the use of strain analysis.

The Railways Administration carried out a very thorough investigation into the stresses set up in a locomotive under load, pulling up a heavy gradient. In this case the strain gauges were affixed to the strategic points on the steel frame, on the coupling rods, connecting rods, slide bars and various other points. The locomotive was tested after a complete overhaul with everything tight and properly adjusted and the stresses set up were calculated. Various bushes were then turned down to represent conditions of wear and the same series of tests were carried out. The results were so impressive that a new code of maximum wear clearances was introduced as a result. A further series of tests were carried out to ascertain the loading when coupled wheels took again immediately after slipping. The results of these tests revealed abnormally heavy loading indeed. The strain gauges have been used to test such things as hammer blow on rails and impact loads on bridges.

I regret that I cannot refer you to any books on the two instruments which I have discussed. For the information regarding ultrasonic testing I am indebted to Mr. B. Zenzinger of the South African Bureau of Standards, who lent me Sperry's Technical Data booklet No. 50 - 755. My information regarding strain gauges was obtained from participating in the Railway testing of the locomotives.

Mr. Grant, the Chairman, said that the paper was of most useful practical value. He asked Mr. Gunn if old-age crystallisation would not deter him of re-shelling an old shaft five times. Mr. Grant said that he understood that arrangements were being considered for the Bureau of Standards to visit factories to test shafts.

Mr. Gunn said that he did not think that there would be any difficulty in re-shelling the shaft a fifth time, because the ultrasonic testing, to a certain degree, shewed the crystalline state of the shaft. He mentioned a case of another locally-produced shaft which was full of blow holes and inclusion failures which would be more risky to re-shell.

Mr. Walsh asked Mr. Gunn if he did not think that customers should demand a test on new roller shafts, especially in this country. Defects could involve firms in considerable expense.

Mr. Gunn said that that was a very important point because he knew of two such cases during this past year where local shafts had proved to be defective. The Bureau of Standards, situated in Pretoria, was in a good position to test all locally-produced shafts before they were sent down to the sugar belt.

Mr. Heslop asked what the range of metals which could be tested would be.

Mr. Gunn replied that as far as he knew any metal could be tested. Different frequencies were required for different materials. As far as size was concerned the machine available in South Africa would test up to fifty-four feet.

Mr. Lindemann inquired if the machine could be used on boilers to test for cracks in plates and the like.

Mr. Gunn said that there were other testers available rather than an ultrasonic one. They had a machine, which for instance, could measure fatigue in rivets. It was not an ultrasonic type, but a magnetic one.

Mr. Rault said that we should not wait for the Bureau of Standards to do our testing. He wondered if therefore it could not be done within the industry or some local organisation, rather than wait for the Bureau of Standards. There were three hundred or more rollers requiring testing in the industry and the financial loss occasioned by breakdowns was large.

Mr. Gunn pointed out that not all mechanical breakdowns could be avoided by using the ultrasonic tester. He had been told that any company could hire testing time from the South African Bureau of Standards up to one-hundred-and-fifty hours. This he thought would be a more economical project than buying their own equipment. Such testing would have to be done all at the same time, January or February.

Dr. Douwes Dekker said that he had had a discussion with the Bureau of Standards on the possibility of the Sugar Milling Research Institute having a contracting period of about one-hundred-and-fifty hours for the whole sugar industry. He planned to pursue the matter further.