An apparatus for the measurement of Young's modulus and internal friction of metals

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Abstract. An apparatus is described for the measurement of Young's modulus and the internal friction of metals in the kilocycle per second range. Measurements can be carried out in the temperature range from 100 to 430°K. The apparatus is based on a device recently described. Modifications consist mainly in an improved clamping device and in the addition of a simple electronic circuit for evaluating the internal friction. An electronic counter is used to determine the resonance frequency.

1. Introduction

In measurements of the internal friction of metal specimens in the kilocycle per second range, resonance methods are often used. In consequence of the very small damping coefficients of several metals, particularly of alloys, a direct measurement of the resonance peak makes high demands upon the stability and resolution of the sine-wave oscillator used. Moreover, small changes in specimen temperature during such a measurement cause large errors in the internal friction, as can be concluded from the following example. For a particular sample of beryllium resonating at about 90000 c/s, the quality factor Q appeared to be 9×10^4, and the temperature coefficient of the resonance frequency 10 c/s per degc. It is easily shown that in this case a change in specimen temperature of 0·005 degc during the measurement causes an error in Q of 5%. To avoid these complications, devices have been developed (Dickson and Strauch 1959, Thompson and Glass 1958) in which a 'sing-around' principle is applied. Here the specimen forms the frequency determining element in a regenerative circuit, just as in the well-known tuning-fork oscillator. To find the internal friction, one can either measure the force necessary to keep the vibrations stationary at a known amplitude (Thompson and Glass 1958), or one stops the energy supply and measures the decay time of the vibrating specimen (Dickson and Strauch 1959). Several methods are used to determine this decay time. For very small dampings a stopwatch is often used, while for greater dampings a photograph can be made of the oscilloscope pattern. The evaluation of the damping coefficient from such a photograph, however, is rather time-consuming. An elegant alternative is to measure by an electronic device the time it takes for the amplitude to decay from one fixed level to another. Apart from the rather sophisticated electronics required, this method has the drawback that one cannot see at a glance whether the decay follows an exponential law or not. To check this it is necessary to shift the levels in such a way that their ratio is kept fixed. In the apparatus to be described, an electronic circuit is applied which enables one to measure the internal friction quickly, which is simple to construct, and from which a deviation from an exponential decay can be seen directly.

2. Description of the apparatus

A block diagram of the apparatus is shown in figure 1. It is essentially the one described by Dickson and Strauch. Added are circuit 13, which delivers an exponentially decaying voltage $Ae^{-t/\tau}$, and electronic counter 9. The circuit forms a regenerative loop, which can be put into oscillation by a proper setting of phase-shifter 5 and the gain of amplifier 4. In determining the resonance frequency of the specimen, the

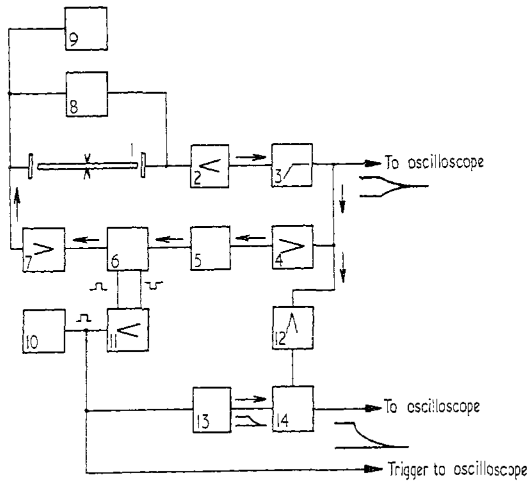


Figure 1. Block diagram of the apparatus.
1, Vibrating specimen; 2, cathode follower; 3, high-pass filter; 4, amplifier; 5, limiter and phase shifter; 6, electronic switch; 7, amplifier; 8, bias supply; 9, counter; 10, adjustable multivibrator; 11, phase inverter; 12, variable amplifier; 13, RC network; 14, adding circuit.

circuit is allowed to oscillate continuously and the resonance frequency is read from the counter. For evaluation of the internal friction, the circuit is provided with electronic switch 6; it can open and close the circuit at predetermined time intervals. As the switch opens, a pulse triggers the oscilloscope time base so that the decaying waveform is displayed on the screen. By network 14, the exponentially decaying voltage $Ae^{-t/\tau}$ is added to this waveform. This decaying voltage is triggered by the same pulse which triggers the time base of the oscilloscope. Decay time τ of this voltage, as well as the initial value of the original waveform, can be adjusted within wide limits. If now factor A and decay time τ equal respectively, the initial amplitude and decay time of the original waveform, the pattern on the oscilloscope screen will have a horizontal line as its bottom; see figure 2. In order to test

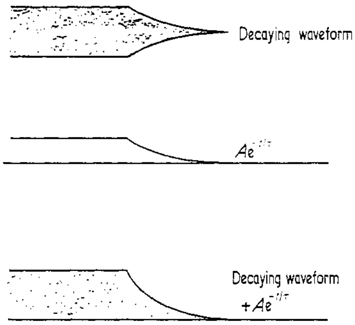


Figure 2. Illustration of the measurement of internal friction.

whether this is the case a very high amplification was applied. Difficulties of overloading, liable to occur in the case of a normal amplifier, were avoided by using a Tektronix type Z plug-in amplifier.

The function of high-pass filter 3 is to prevent parasitic oscillations from occurring. Without this filter, the circuit has the tendency to oscillate at two different frequencies, viz. the proper frequency and a frequency of about 1000 c/s, determined by the mass of the specimen and the stiffness of the clamping screws. The distortion of the decaying waveform by this filter can be neglected.

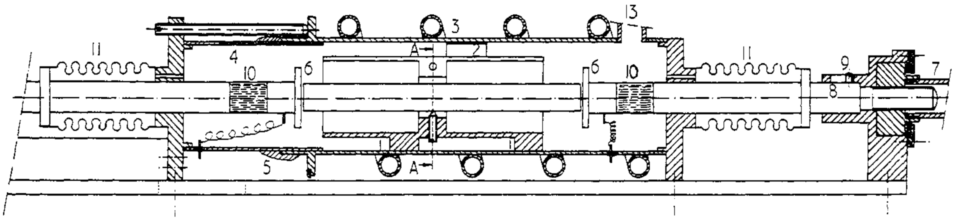


Figure 3(*a*). Outline of the mechanical construction. 1, cams; 2, springs; 3, outer brass tube; 4, inner brass tube; 5, elastic putty; 6, electrodes; 7, driving tube; 8, electrode rod; 9, pin; 10, insulating blocks; 11, bellows; 13, vacuum connection.

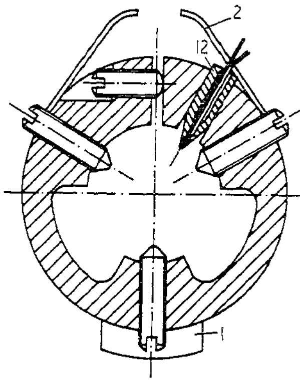


Figure 3(*b*). Details of the clamping device, cut through A-A of (*a*).
1, cams; 2 springs; 12, thermocouple.

3. Mechanical construction

The mechanical construction of the apparatus is schematically shown in figure 3 (*a*) and (*b*). The specimen is clamped in the sample holder by means of three screws. The sample holder is made up of a steel cylinder which is cut through in the length direction, so that it acts as a spring. This construction has the advantage that, notwithstanding differences in thermal expansion of the sample and the different parts of the holder, the sample will always stay clamped. In an earlier version of the apparatus, in which this construction was not applied, it sometimes happened that the sample was loosened when, after cooling from room temperature to 100°K, the apparatus was allowed to warm up again to room temperature. This was probably due to permanent deformation of the sample by the clamping screws during the cooling period. The sample holder is guided by means of two cams 1 and two springs 2 in brass tube 3, which in its turn fits sliding over brass tube 4. A vacuum-tight connection between these two brass tubes could be obtained, in the experimentally covered temperature range, by a layer of elastic putty 5 ('Raam en stopkit', N. V. Saba, Dinxperlo, The Netherlands). Electrodes 6 can be moved with respect to the specimen with the aid of the two tubes 7. Rotation of electrode rods 8 is prevented by pins 9. The electrodes are electrically insulated from rods 8 by insulating blocks 10. By the insertion of rods between these insulation blocks and the electrodes, specimens down to about 40 mm can be measured, the maximum length without these rods being 105 mm. The application of bellows 11 allows the movements of the electrodes without disturbance of the vacuum in the apparatus. The vacuum was obtained by means of a rotating oil pump. An ultimate pressure of 30 mtorr was reached, which proved to be sufficient for the highest quality factors ($Q = 90000$) encountered so far.

4. Temperature control

On the outside, brass tube 3 is provided with a spiral made of copper tubing. To cool the specimen, liquid nitrogen is evaporated in a Dewar by an electrical heating element, and the vapour is forced through this spiral. Temperatures as low as 110°K can be reached in this manner, without using excessive amounts of liquid nitrogen. For one run from room temperature to 110°K, the amount of liquid nitrogen needed is about 10 l. The current through the heating element is controlled by a Variac and is normally adjusted so as to cause a rate of cooling of 0·5 degc min^{-1}. To prevent overloading of the heating element, the current through it is interrupted as soon as the level of the liquid nitrogen drops too low. To this end, a thermocouple is fitted in the Dewar, one junction of which is located at the bottom of the Dewar, the other at the height of the top of the heater. When the liquid nitrogen level drops below the latter junction a small d.c. signal appears over the thermocouple, which, after amplification, drives a relay. For measurements above room temperature preheated air is forced through the spiral. The maximum admissible temperature is determined by the softening point of the solder with which the different parts of the apparatus are soldered together, and which in the present apparatus is 430°K. The temperature of the specimen is measured with thermocouple 12 in direct contact in its nodal plane. The thermocouple wires leave the apparatus through a groove in tube 4.

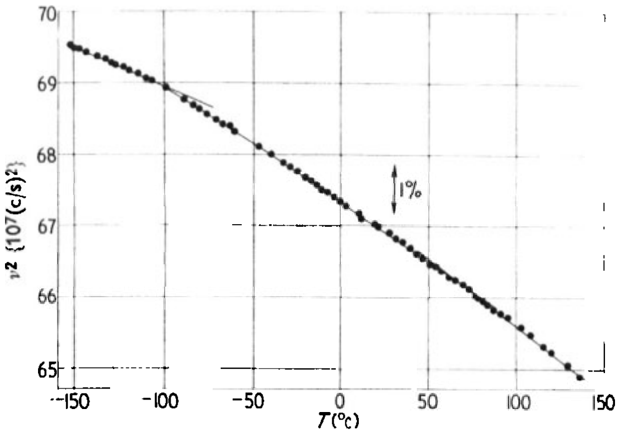
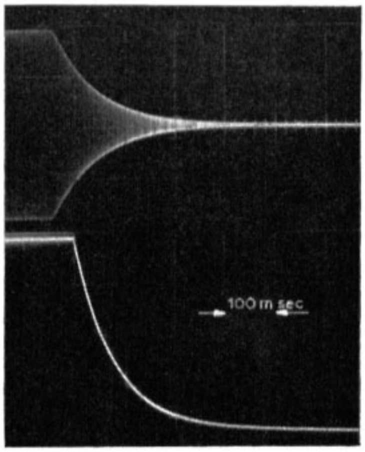


Figure 4. ν^2 plotted against temperature for a polycrystalline iron sample.

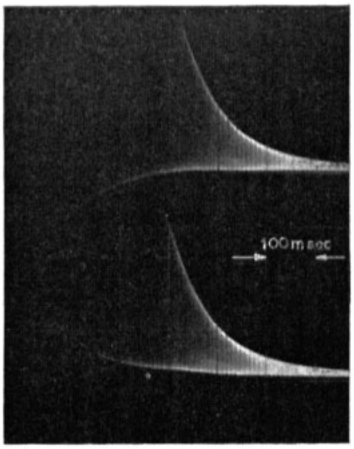
5. Measuring procedure and performance of the apparatus

5.1. *Young's modulus*

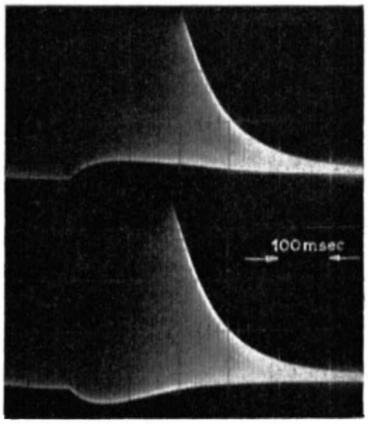
In measuring the resonance frequency of the specimen the electronic switch is rendered inoperative and the circuit put into oscillation by adjustment of the phase shifter and the amplifier gain. The frequency range in which oscillation can occur is quite narrow. As an illustration, a particular specimen with a quality factor Q of about 90000 could be forced to vibrate in the frequency range from 90223·4 to 90218·6 c/s. For these extreme values it was clearly visible (by the small amplitude of the oscillation) that the specimen did not vibrate at the proper frequency. However, the error thus made in the measurements is thought not to exceed 0·2 c/s. Also, the resonance frequency does not depend critically on small departures of the plane of the clamping screws from the nodal plane. A misadjustment of two millimetres for a specimen of 100 mm length resulted in an error of about one part in 10^4 in the resonance frequency.



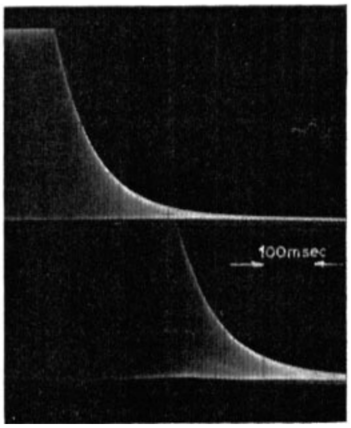
(*a*) Top: decaying wave form; bottom: voltage $Ae^{-t/\tau}$.



(*b*) Top: gain of amplifier 12 too large; bottom: gain of amplifier 12 too small.



(*c*) Amplifier 12 adjusted correctly. Top: τ 5% too large; bottom: τ 5% too small.



(*d*) Amplifier 12 and τ adjusted correctly. Top: complete signal; bottom: lower part of the signal at a magnification of 20 ×.

Figure 5.

Notes: 1. In all oscillograms the main divisions equal 1 cm. 2. The resonance frequency of the sample was about 26000 c/s. The nearly vertical lines are, therefore, not the individual sine waves, although this can appear to be so at first sight. Actually, these lines are caused by an incidental 50 c/s intensity modulation.

Young's modulus E can be found from resonance frequency ν by the relation

$$E = 4\rho L^2 \nu^2 \dagger \qquad (1)$$

in which ρ and L are density and length of the specimen, respectively.

The error in ν due to the uncertainty of the counter will be ± 1 count. As a counting time of one second was commonly used, this amounts to about 1 part in 2×10^4 for ν or 1 part in 10^4 for ν^2. This is still an order of magnitude greater than the error made by misadjustment of the sample. Thus in absolute measurements the values of ρ and L must be known very accurately to make the most of the possibilities of the method. In studying the change of Young's modulus with temperature this is not the case. In practice it is found that if no phase transitions occur in the temperature range of interest the temperature dependence of ρL^2 is small compared with the temperature dependence of E. Therefore, as an illustration, in figure 4 ν^2 is plotted against temperature for a technical steel. As can be seen from this figure the scatter of the measuring points does not exceed $0{\cdot}4‰$. This scatter is caused by the errors in the temperature measurements, and possibly by departures from thermal equilibrium of the sample.

5.2. *Internal friction.*

In determining the internal friction, the electronic switch is put into operation and the pattern is viewed on the oscilloscope. Now variable amplifier 12 and decay time τ of network 13 have to be adjusted so as to make the lower boundary of the pattern a horizontal line. Although in principle these parameters can be adjusted independently, an alternative adjustment was found more convenient. First variable amplifier 12 is adjusted coarsely, the criterion for a good setting being that the lower boundary starts at the same level as it ends. Next the decay time is adjusted so as to make this boundary as straight as possible. Repetition of this procedure once suffices for the final setting. In performing measurements as a function of temperature, the internal friction changes gradually and only small readjustments of 12 and 13 are necessary. In practice it appeared to be feasible to determine both the resonance frequency and the internal friction once every minute. In figure 5 oscillograms are given for different settings of 12 and 13. From these oscillograms it follows that a deviation of 5% from the real value of τ is easily detected. It is hard to give an exact value of the error made by incorrect adjustments, as it depends to some extent on the sample in question. Even under unfavourable conditions, however, this error will not exceed 2%.

† Formula (1) is a first order approximation which holds for $L/D \gg 1$, where D is the diameter of the specimen. For better approximations see for example Kolsky (1953).

Acknowledgments

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