15. *Study on the Coefficient of Internal Friction of Materials used in Civil Engineerings and Architectural Structures. (1st Report)*

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1. Purpose.

It is well known that for earthquake-proofing the absorption of energy in a vibrating structure is a factor as important as the natural period or stiffness of the structure or its members. In this respect, we must pay attention to the damping of vibration of structures. The damping is usually caused by the external friction, escapement of energy from the foundation to the ground and also by the viscous properties of materials of the structure. So it is important to know the coefficient of internal friction of materials used in structures, and further, we must measure the energy dissipaton at various joints in the structures.

In these views, the writer measured, as the first step of his study, the coefficient of internal friction of several materials commonly used in civil engineering and architectural structures.

Although there are many studies on the internal friction, they are almost of metals and gases. Moreover, the methods of experiment are to measure the damping of longitudinal or transversal vibration of specimen in vacuum, cramping one end of the specimen and exciting the other end. But it is the deficiency of these previous experiments that the energy escapement from the fixing point was neglected.

So the writer has designed an apparatus which is free from such deficiency, and has measured the coefficient of internal friction of several materials such as metals, glass, woods and ebonite.

2. Apparatus.

The specimen which we want to measure is cut into such a shape as shown in Fig. 1. Two brass disks are cramped to the both ends of the specimen. Upper disk is two times thicker than the lower, and from the opposite surfaces of the two disks, two pairs of brass arms, strong enough compared with any specimen, are equipped. Each of the upper arm has an electro-magnet, and

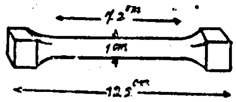


Fig. 1.

at the upper part of each of two lower arms, thin iron plates are soldered facing to the electro-magnets. These conditions are shown in Fig. 2.

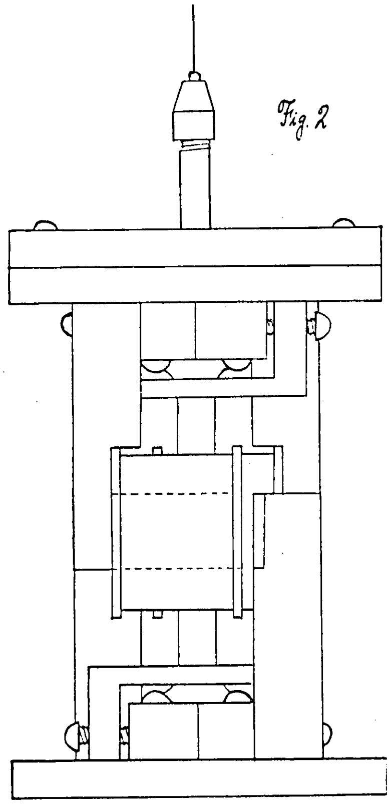


Fig. 2

This vibrating system is suspended by a piece of thin piano wire (0.35 mm in dia.) in a bell-jar. The core of magnet and thin iron plates are of pure iron so as not to produce residual magnetism. Lead wires of the magnet coils are fine springs which do not give any tension to the coil. (By these arrangements, the vibrating system is practically isolated.)

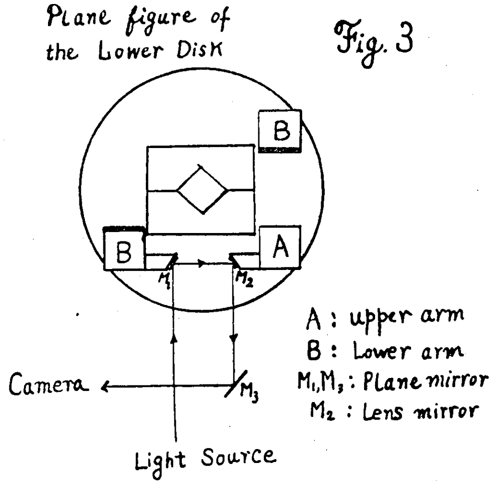


Fig. 3

The recording system of damping vibration is as follows. As shown in Fig. 3, the light from a straight line filament lamp is reflected by a plane mirror and a lens mirror, which are soldered to the opposite ends of lower and upper arms, and then reflected once more by a plane mirror at the outside of the bell-jar, making an image of the filamnt on the recording film wound on a revolving drum. Time marks of each second are also recorded on the same film. By means of these mirror system, we can record only the relative torsional deflection of the two disks.

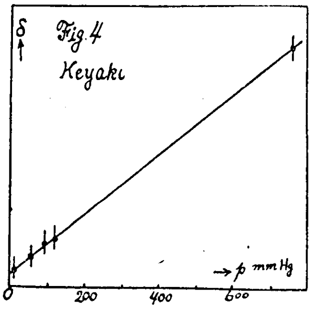
3. Method of Measuring.

The damping of these torsional vibration is due to the friction of air and to the viscous properties of the specimen.

So if the experiment is performed in a vacuum, the damping is wholly due to the latter quantity, and we can obtain the coefficient of internal friction, free from other factors.

By means of a momental excitation due to the electro-magnet, two opposite arms, each of which has an iron plate, are attracted instantly and after that the system begins its natural vibration, the period of which depends on the rigidity of the specimen. The records obtained are such as shown in Fig. 8.

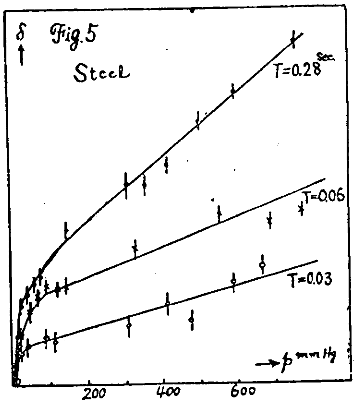
If the dimension of the specimen is large, this apparatus can not be applied and need a larger vessel such as an oil-can. In such a case, high vacuum would be difficult to be obtained. So we must know the relation between the logarithmic decrement δ and the pressure of air p. This relation in the case of *keyaki* (zelkova tree) is as Fig. 4. It is exactly linear.

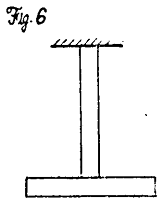


Next it is necessary to know the relation between the period of vibration and the air pressure. The relation was obtained by using specimens (cold drawn steel wires) of different diameters. (Fig. 5.).

The facts which can be inferred from these results are as follows.

1. The shorter the period, the smaller the effects of air upon δ.
2. From 0 mmHg to 20 mmHg, relation between δ and p is almost linear. So we can deduce the value of δ corresponding to zero pressure from several measurements done in the range of 0 mmHg to 20 mmHg.





4. Results of Experiment.

As is shown in Fig. 6, if the upper end of specimen is fixed and the other end carries the disk of which the moment of inertia is I, which is large compared with that of the specimen, the internal friction of the specimen acting as a damping force, the equation of free vibration of this disk is

$$I\frac{d^2\theta}{dt^2}+\alpha\frac{d\theta}{dt}+\beta\theta=0 \qquad (1)$$

where α is a constant depending on the coefficient of internal friction and energy escapement, and

$$\beta=\frac{\pi n R^4}{2l},$$

in which n, R, l are respectively the torsional rigidity, the radius and the length of specimen.

Solution of the above equation is

$$\theta=\theta_0 e^{-\frac{\alpha t}{2I}}\cos\left(\frac{2\pi t}{T}+\varepsilon\right)$$

When we consider that the 2nd term of equation (1) is dependent only on the viscosity, α becomes as follows:

$$\alpha=\frac{\pi\eta R^4}{2l},$$

where η is the coefficient of tangential viscosity of the specimen.

Since the period of this system is

$$T=2\pi\Big/\sqrt{\frac{\beta}{I}-\left(\frac{\alpha}{2I}\right)^2},$$

we have

$$\eta=\frac{8\delta l I}{\pi R^4 T}$$

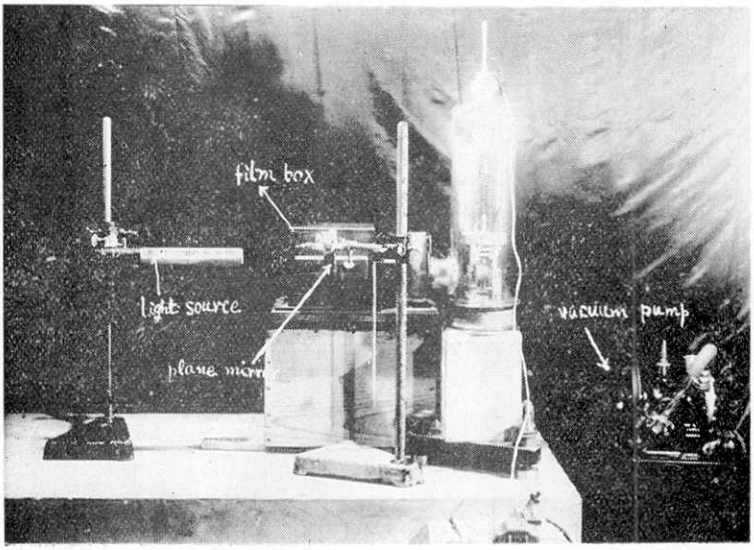
As the values of δ, I, l, R, T can be obtained from our experiments, we can determine the value of the coefficient of tangential viscosity η.

Next, consider the case of our vibrating system—that is the specimen carrying the disk at both ends. The moment of inertia of the upper disk is $I_1(=32535\ c.g.s.)$ and of the lower one is $I_2(=16458\ c.g.s.)$ respectively.

Then η becomes as follows:

$$\eta=\frac{8\delta l I_1 I_2}{\pi R^4 T(I_1+I_2)}$$

According to the experiments, the logarithmic decrements of torsional vibration are in these two cases clearly different—the decrement in the former case is larger than the decrement in the latter. The apparent



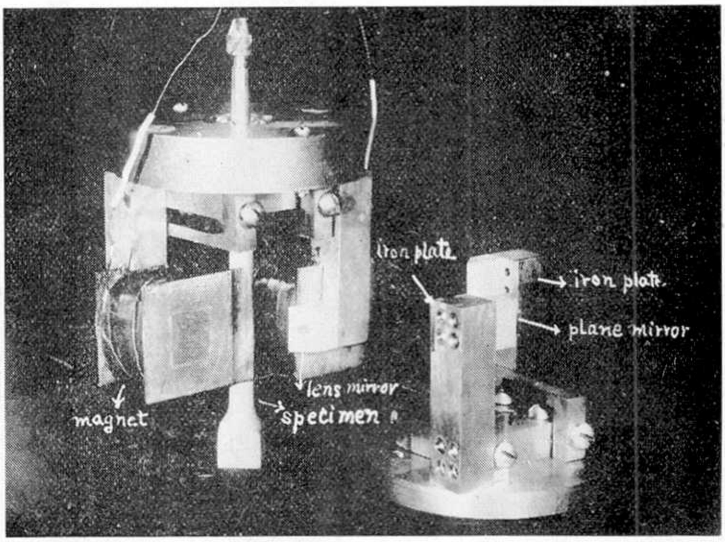


Fig. 7.

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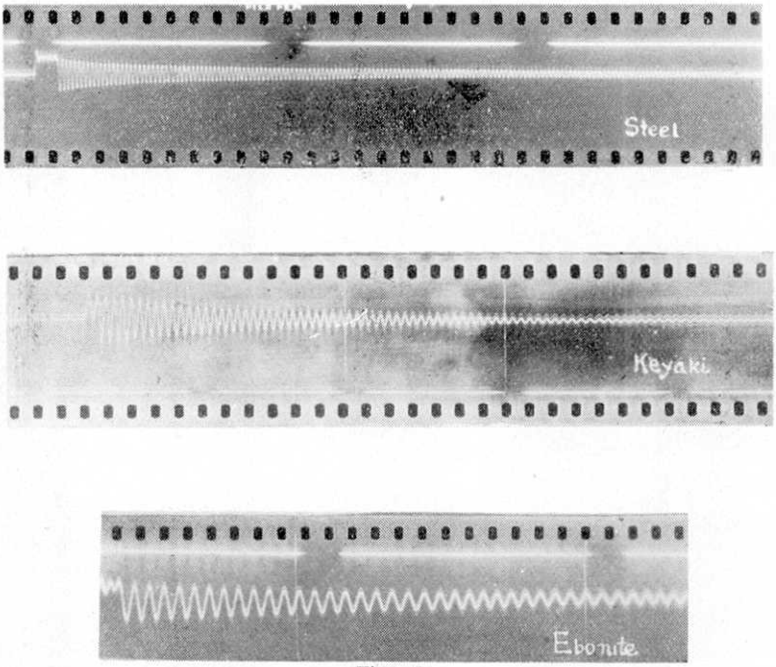

Fig. 8.

internal friction accordingly became much larger in the case of the former experiment. This is clearly due to the energy which escaped from the fixed point in the former case.

The value of coefficient of tangential viscosity of the above two cases was as follows:

The former: 2.396×10^6 (*c. g. s.*)
The latter: 0.937×10^6 („)

According to the theory of torsional vibration, the decrement is independent of the amplitude of vibration, but in reality the logarithmic decrement at the beginning of the vibration decreases linearly with its amplitude and only when the amplitude become small enough, the decrement becomes constant. If the angle of twist of specimen is very small, the logarithmic decrement is independent of its amplitude.

Several results which have been obtained are as follows:

specimen	dia.	temp.	η (*c. g. s.*)
steel	0.15 cm	14°C	0.44×10^6
aluminium	0.18	14	0.43
ebonite	1.00	13.5	0.58
keyaki	1.00	21	0.69
sugi (Cryptomeria)	1.00	21	0.72

Air pressure is in all cases 0 mmHg.

The purpose of this experiment is to find out material which has a large value of η and large rigidity, because for the purpose of earthquake-proofing of structures, the quantity $\eta \times n$ must be large.

In conclusion, the writer wishes to thank Prof. R. Takahasi for his advice and helpful criticism.