METHODS OF TESTING VULCANIZED RUBBER

PART A24. DYNAMIC TESTING OF VULCANIZED RUBBER

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Committee references RUC/10 and RUC/10/4
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BRITISH STANDARD

METHODS OF TESTING VULCANIZED RUBBER

Part A24.

Dynamic Testing of Vulcanized Rubber

FOREWORD

This British Standard has been published under the authority of the Rubber Industry Standards Committee. In deciding to issue a revision of the 1950 edition of B.S. 903 it has been considered desirable to publish it in separate parts, and the present part gives a hitherto unpublished determination.

The group of parts in which the prefix letter ' A ' is used covers methods of testing the physical properties of rubber.

NOTE. Where metric equivalents are stated, the figures in British units are to be regarded as the standard. The metric conversions are approximate. More accurate conversions should be based on the tables in B.S. 350, ' Conversion factors and tables '.

SECTION 1. SUMMARY AND EXPLANATORY NOTES

1.1 The dynamic test procedures described below are intended to measure the visco-elastic (dynamic) properties of vulcanized rubber by causing it to undergo cyclic deformations of controlled frequency and amplitude.

1.2 These procedures cover the testing of (i) specially prepared test pieces, for the purpose of determining the basic visco-elastic properties of the rubber, and (ii) finished products or scaled-down models of them, normally to determine their load-deflection and damping characteristics.

1.3 The present document sets out the general requirements which any satisfactory dynamic test apparatus and procedure must fulfil. It is not intended that all the ranges of test conditions shall be covered by a single piece of apparatus; hence two or more different types will in general be needed. Descriptions of recommended dynamic test machines are given in Appendix C; these are given as examples, and their use is not mandatory.

1.4 The visco-elastic behaviour of vulcanized rubber is dependent on the temperature, the frequency of the cyclic deformations, and the amplitude of these cycles. Hence for a full assessment of this behaviour the variation of the visco-elastic properties with all three of these variables must be known.

1.5 Variation of amplitude is essential because with compounded (especially carbon black) rubbers the elastic modulus may vary considerably with amplitude, so that tests should be made at amplitudes corresponding to the service conditions, where known. Very small amplitudes (say less than about 0·1 per cent, depending on the rubber) should be avoided unless they correspond to service conditions, because in this region the modulus is so high that its value is not representative of behaviour at larger amplitudes. (See Appendix A.)

1.6 Rubbers containing reinforcing fillers, especially carbon black, show changes in properties due to breakdown of structure when deformed. In testing such a rubber, it must therefore first be pre-stressed by deforming to at least the maximum strain imposed by the test, in order to remove the temporary stiffness due to this structure. In tests using a continuous train of cyclic deformations, this pre-stressing is conveniently done by running the test for a sufficient period for the readings to become substantially constant. If the pre-stressing is carried out as a separate operation, it must be done at the test temperature, and the test must be made as soon as possible after the pre-stressing; this is especially important at elevated temperatures, where structure re-formation may be relatively rapid.

1.7 The effects of temperature and frequency are related, as described in Appendix B, so that it may not be necessary experimentally to cover the whole ranges of both these variables. When the behaviour of the rubber is non-linear, that is, the elastic and viscous components are not Hookean and Newtonian respectively, this temperature/frequency relationship is not strictly valid, but nevertheless applies to normal rubbers to a sufficient approximation.

1.8 In general, the modulus measured over cycles of relatively high frequency (*complex modulus*) is greater than the *mean modulus* or slope of the substantially static stress-strain curve at the point around which the cycles are executed. Hence both complex and mean modulus values must be measured.

1.9 As the visco-elastic properties of vulcanized rubber vary with temperature, the test conditions must be such as not to produce appreciable temperature rise in the rubber unless the actual temperature inside the test piece is measured. For a given rubber and test period this temperature rise increases with increase of frequency, amplitude and test piece dimensions; hence, it will not in general be feasible to use in combination the highest values specified below for all of these variables, though these values may be permissible individually if other circumstances permit.

SECTION 2. DEFINITIONS

For the purposes of this British Standard the following definitions apply:

2.1 Mean stress. The constant stress upon which the deformation cycles are superimposed, that is, the stress corresponding to the mid-point X of the cycles. (See Fig. 1.)

2.2 Mean strain. The constant strain upon which the deformation cycles are superimposed, that is, the strain corresponding to the mid-point X of the cycles. (See Fig. 1.)

2.3 Mean modulus. Slope of the tangent FG to the substantially static stress/strain curve OXB at the mid-point X of the cycles. (See Fig. 1.)

2.4 Complex modulus. Ratio of stress amplitude to strain amplitude in the cycles, that is, the slope of the line DE joining the points of intersection of the vertical and horizontal tangents to the loop. (See Fig. 1.)

2.5 In-phase (or dynamic) modulus. The component of the complex modulus corresponding to the stress component that varies in phase with the applied strain; curve 1, Fig. 2.

2.6 Out-of-phase (or loss) modulus. The component of the complex modulus corresponding to the stress component 90° out of phase with the applied strain; curve 2, Fig. 2.

2.7 Loss angle. Angle δ by which the cycles of total stress are displaced relative to the in-phase stress (and strain) cycles. (See Fig. 2.)

2.8 Loss tangent. Tangent of the loss angle. If the amplitudes of the in-phase and out-of-phase stress cycles are A_1 and A_2 respectively (see Fig. 2), then $\tan \delta = A_2/A_1$.

2.9 Energy loss. The energy lost per cycle of dynamic deformation, i.e. the energy represented by the area of the loop in Fig. 1.

2.10 Mean stiffness. The slope of the force/deformation curve of a piece of rubber or a manufactured rubber unit at the point corresponding to the centre of the cycles, that is, the slope of FG in Fig. 1 with stress and strain replaced by force and deformation respectively. Mean stiffness is thus expressed in lbf/in or kgf/cm.

2.11 Complex stiffness. The ratio of the force amplitude to the deformation amplitude in the cycles, for a piece of rubber or a manufactured rubber unit, that is, the slope of DE in Fig. 1 expressed in lbf/in or kgf/cm.

SECTION 3. PROPERTIES TO BE MEASURED

3.1 Prepared test pieces. In general, such test pieces will be used to determine the following basic properties, and the test apparatus must therefore enable these to be measured:

Mean modulus.
Complex modulus *or* in-phase modulus.
Damping (*either* out-of-phase modulus *or* loss angle *or* loss tangent *or* energy loss).

3.2 Manufactured products or scaled-down models. In tests on finished products or models it will more often be required to determine the following properties:

Mean stiffness
Complex stiffness
Energy loss

SECTION 4. APPARATUS

The test apparatus shall be capable of making tests involving compression, tension or shear of the rubber.

It shall be capable of applying the appropriate mean strain and deformation cycles at a frequency and temperature within the limits laid down below.

4.1 Range of mean strain. The mean strain shall be the required value up to the following:

Compression	20 per cent
Tension	20 per cent
Shear	50 per cent

Preferred values of mean strain are given in Table 1.

TABLE 1. MEAN STRAIN

	per cent
Compression or tension	0, 5, 10, 15, 20
	per cent
Shear	0, 10, 20, 30, 40, 50

4.2 Deformation cycles.

4.2.1 *Form of cycles.* The deformation cycles shall be in the form of *either* a continuous wave train *or* a regular succession of separate deformations in the same direction, each corresponding to approximately one half-cycle.

The test machine may apply either strain cycles or stress cycles. If these are in the form of a continuous wave train the wave form shall be sinusoidal within limits defined as follows:

> With time plotted horizontally the ordinate at any point on the curve representing the wave form shall not differ from the corresponding ordinate of a sinusoidal curve having the same peak value, by more than 5 per cent of this value.

If stress cycles of large amplitude are applied care is needed to ensure that the wave form is not disturbed by resonance in the apparatus. If the rubber is deformed by a succession of separate half-cycles these may conveniently be produced by rotation of an annulus of the rubber pressed against a freely rotating rigid member.

4.2.2 *Forced or free vibrations.* When the test piece is subjected to strain cycles their amplitude should remain substantially constant during the test because of the amplitude effect referred to in Clause 1.5. For this reason forced vibration machines are preferred to those of the free vibration type, since in the latter, unless special precautions are taken, the amplitude decays owing to damping, causing a change in frequency.

4.2.3 *Stress or strain cycles.* Strain cycles may be imposed and the resulting stress variations recorded, or vice versa. In general, excepting when amplitude is very small, the former procedure is preferable because it is easier to achieve sinusoidal wave form for an imposed strain than for an imposed stress.

4.2.4 *Amplitude.* The applied strain shall have the required amplitude up to the value shown in Table 2.

TABLE 2. STRAIN AMPLITUDES

	Continuous wave train (1)	Succession of half-cycles (2)
Compression	± 5 per cent	25 per cent
Tension	± 5 per cent	—
Shear	± 20 per cent	—

Preferred values of amplitude are given in Table 3.

TABLE 3. STRAIN AMPLITUDES

	per cent
Compression (1) Tension	0·1, 0·3, 1·0, 2·5, 5
	per cent
Compression (2) Shear	0·3, 1·0, 2·5, 5, 10, 20

4.3 Frequency and temperature ranges. The properties indicated in Section 3 shall be determined over the required range within the following limits:

Frequency: 0·1 to 200 c/s.
Temperature: −70°C to 200°C.

(The lower temperature and higher frequency limits will not be possible with all rubbers since rubbers with relatively high glass transition temperature would be semi-rigid.)

Preferred frequencies and temperatures are given in Table 4.

TABLE 4. FREQUENCIES AND TEMPERATURES

Frequency c/s	0·1 1 10 100 200
Temperature °C	−70, −55, −40, −25, −10 0, 20, 50, 70, 100, 125, 150, 175, 200

NOTE 1. In the ' transition ' state of the rubber smaller frequency or temperature steps may be needed: e.g. $\sqrt{10}$ for frequency, or 5 degC for temperature.
NOTE 2. The list of temperatures is that proposed by ISO/TC 45, with the addition of − 70° and 0°, and the omission of 23° and 27°.

4.4 Force measurement. Where sinusoidal strain cycles are imposed, the device for measuring the instantaneous force shall not involve movements of the fixed end member large enough to disturb the sinusoidal form of the cycles.

SECTION 5. TEST PIECES

5.1 Prepared test pieces.

5.1.1 *Compression test piece.* A cylinder not greater than 1½ in (38 mm) high or 2½ in (64 mm) in diameter; preferably with height equal to diameter. Normally the ends of the test piece shall be bonded to flat metal members but, if desired, tests may be made with the ends lubricated to give substantially complete slip.

For compression tests involving repeated but separate part-cyclic deformations (see Clause 4.2.1 and Fig. 7) the test piece may have the form of an annulus of rectangular cross-section with a rigid (metal) core. (The deformation is produced by rotation against a rigid wheel.)

5.1.2 *Tension test piece.* A cylinder not greater than 4 in (101 mm) long or 2½ in (64 mm) in diameter, with the ends bonded to metal members suitable for attaching to the grips of the test machine.

5.1.3 *Shear test piece.* The preferred test piece is a cylinder 1 in (25 mm) in diameter and 0·25 in (6·3 mm) thick. Alternatively, a rectangular block 1 in (25 mm) square by 0·5 in (12·5 mm) thick may be used. In either case the larger faces are bonded to flat metal members, and it is convenient to use four test pieces, as shown in Fig. 8, so as to allow for applying a mean strain (or mean stress) in shear or in compression.

5.2 Manufactured products or models. The test machine should be capable of testing units or models up to the following sizes:

Cross-section of rubber: 5 in² (32 cm²).
Largest dimension of cross-section of rubber: 4 in (101 mm).
Height of rubber: 1½ in (38 mm) for compression or shear, 4 in (101 mm) for tension.
Largest dimension of complete unit: 6 in (152 mm).

APPENDIX A

AMPLITUDE EFFECT

Fig. 3 illustrates the magnitude of the amplitude effect; curve 1 shows the behaviour of a natural rubber pure gum vulcanizate, and curves 2 to 7 refer to vulcanizates with increasing proportions of a reinforcing carbon black.

The right-hand parts of the amplitude-modulus curves are substantially straight, and for many rubbers can be represented, over the amplitude range about 3 to 50 per cent, by the following empirical equation:

$$E = E_0\,(A/A_0)^{-n}$$

where E is the modulus at any given strain amplitude A;

E_0 is the modulus at an arbitrary fixed amplitude A_0, e.g. 10 per cent;

n is a coefficient ranging from zero for natural rubber pure gum vulcanizates to about 0·6 for carbon black vulcanizates or some synthetic rubbers (see Ref. 1).

APPENDIX B

INTER-RELATION OF TEMPERATURE AND FREQUENCY EFFECTS

The moduli of vulcanized rubber are affected similarly by lowering (raising) the temperature and by increasing (decreasing) frequency. Moreover, the temperature change and frequency change required to produce the same effect are related. This relation can be approximately expressed in the following way:

(i) It is first necessary to correct all modulus values to an arbitrary reference temperature T_r (e.g. 273°K) by multiplying by $T_r d_r/Td$ where d and d_r are the densities of the rubber at temperatures T and T_r (°K). The value so corrected is called the ' reduced modulus '.

(ii) If, starting with measurements at temperature T and frequency ω, a change of temperature from T to T_1 (frequency remaining at ω) produces the same change in reduced modulus as a change of frequency from ω to ω_1 (temperature remaining at T), then

$$\log(\omega_1/\omega) = \frac{900\,(T - T_1)}{(102 + T_1 - T_s)\,(102 + T - T_s)}$$

where T_s is a ' characteristic temperature ' depending on the nature of the polymer and to a less extent on its vulcanization and compounding (see Ref. 2).

APPENDIX C

RECOMMENDED DYNAMIC TEST MACHINES

I. SINUSOIDAL-STRAIN MACHINE (REF. 2)

Apparatus.

General construction. Two anvils A_1 A_2 (Fig. 4) are driven with a sinusoidal motion by rotation of eccentric B in block C, free to slide vertically in the crosshead D. Two 'fixed' anvils A_3 A_4 are mounted so that the spaces A_1–A_3 and A_2–A_4 can be adjusted.

The eccentric shaft carries a flywheel E with sufficient moment of inertia to maintain the rotational speed substantially constant in spite of the variable resultant force from A_1 and A_2.

The throw of the eccentric can be adjusted between $\pm$ 0·001 in and $\pm$ 0·25 in, and the speed between 0·0001 and 30 c/s.

The rubber test piece F is inserted between A_2 and A_4, fittings being provided for deforming it in shear, compression (as shown), tension or shear-plus-compression. The mean strain on the test piece is controlled by adjusting the position of A_4. Anvils A_2 and A_4 and the test piece can be surrounded by a thermostat chamber giving temperatures between $-$ 70°C and $+$ 200°C controlled to within $\pm$ 1 degC.

A helical tempered steel spring G is used to record the strain cycles as described below.

Behind anvils A_3 and A_4 are proof rings H_1 and H_2, the deformations of which are converted by transducers into electrical signals that can be displayed on a cathode ray tube to indicate the forces on the spring and test piece respectively.

The machine can measure stiffness up to 4×10^6 lbf/in ($7{\cdot}2 \times 10^5$ kgf/cm) and loss angles up to any value.

Device for measuring loss angle (for frequencies between 0·05 and 30 c/s). The eccentric shaft carries a disc of electrical insulating material J (Fig. 5) having two metal inserts K_1 K_2 at 180° apart. A capacity probe L, loosely rotatable about the shaft, registers a change in capacity when an insert passes it. This change, amplified by a proximity meter, is fed to the cathode ray tube so as to produce a horizontal displacement of the trace.

With the (horizontal) time base of the tube in operation, the trace would be as Fig. 6 (*a*), but with the time base inoperative, as at (*b*). By moving the probe to a suitable position, the two pulses coincide, as at (*c*). A scale of degrees M is provided.

Procedure.

Measurement of mean strain. The mean strain is derived from the dimensions of the test piece and the initial deformation applied by anvil A_4.

Dynamic strain and stress amplitudes. The strain amplitude is calculated *either* from the throw of the eccentric and dimensions of the test piece, *or* from the amplitude of the signal from proof ring H_1 and the characteristics of spring G.

The force amplitude is derived from the signal from proof ring H_2; this amplitude divided by the cross-sectional area of the test piece gives the stress amplitude.

Measurement of loss angle. The signal from proof ring H_2 is fed to the cathode ray tube, and the probe adjusted to make the pulses coincide as in Fig. 6 (*c*); the position of the probe on scale M is noted.

The signal from proof ring H_1 which is in phase with the strain, is now fed to the tube and the probe readjusted till the pulses again coincide. The angular difference between the two positions of the probe is the loss angle.

Calculation of results.

Symbols:

G^* = complex shear modulus
G' = in-phase shear modulus
G'' = out-of-phase shear modulus
Δ = strain amplitude
Σ = stress amplitude
e = mean compression or tension strain
h = height (dimension perpendicular to stress) of shear test piece
k = radius of gyration of cross-section about neutral axis of bending
s = shape function† for tests in compression with bonded test-piece ends (see Table 5); if lubricated ends are used $s = 1$
$\lambda_1\ \lambda_0\ \lambda_2$ = min., mean and max. heights (lengths) divided by initial height (length).

NOTE. The following equations are in terms of ***shear*** modulus, but to a first approximation could be written using Young's modulus E, equal to 3 G.

Complex modulus.

From shear tests: $G^* = (\Sigma/\Delta)(1 + h^2/36k^2)$ (1)

NOTE. If h is less than about half the cross-sectional dimensions, the $h^2/36k^2$ term may be neglected.

From compression tests: $G^* = 2\Sigma/s\,(\lambda_1^{-2} - \lambda_1 - \lambda_2^{-2} + \lambda_2)$ (2)

NOTE. If Δ is less than 0·1 of the mean compressed height, λ_0, the above simplifies to:

$$G^* = \Sigma/\Delta s\,(1 + 2\lambda_0^{-3}) \qquad \text{(2A)}$$

From tension tests: $G^* = 2\Sigma(\lambda_1 - \lambda_1^{-2} - \lambda_2 + \lambda_2^{-2})^{-1}$ (3)

NOTE. If Δ is less than 0·1 of the mean stretched length λ_0, the above simplifies to:

$$G^* = \Sigma/\Delta\,(1 + 2\lambda_0^{-3}) \qquad \text{(3A)}$$

† Ideally this is the ratio between the forces (or stresses) required to compress the same piece of rubber to the same extent *firstly* with bonded ends and *secondly* with perfectly lubricated ends. In practice a function of the test piece dimensions is generally used as a sufficient approximation to this ratio. (The term ' shape factor ' then denotes some simple relation between the lateral and lengthwise dimensions, e.g. in Table 5 for a square cross-section, the shape *factor* is a/h.)

TABLE 5. EXPRESSIONS FOR SHAPE FUNCTION

In all formulae h = height, i.e. in direction of compression

Cross-section	Shape function
Square side = a	$1 + B(a/h)^2$
Circle diameter = d	$1 + B(d/h)^2$
Rectangle long side = l short side = w	$\dfrac{1{\cdot}33 + 0{\cdot}66w/l + C(w/h)^2}{1 + w/l}$
Annulus outer diameter = d_2 inner diameter = d_1 Case 1: d_2 much greater than d_1 Case 2: d_1 almost as large as d_2	 $1 + B(d_2 - d_1)^2/h^2$ $1{\cdot}33 + D(d_2 - d_1)^2/h^2$
Hollow square outer side = a_2 inner side = a_1 Case 1: a_2 much greater than a_1 Case 2: a_1 almost as large as a_2	 $1 + B(a_2 - a_1)^2/h^2$ $1{\cdot}33 + D(a_2 - a_1)^2/h^2$

Variation of B, C, and D with shear modulus, G, in lbf/in²

$G < 100$	100–150	150–200	200–300	> 300
B 0·120	0·103	0·080	0·063	0·056
C 0·26	0·225	0·175	0·14	0·12
D 0·065	0·056	0·044	0·035	0·030

II. ROTARY POWER LOSS MACHINE (REF. 1)

A rubber annulus (1) of square cross-section, attached to a metal centre (2), is mounted on a freely rotating shaft (3); see Fig. 7. By means of the loaded lever (4) the rubber test piece is pressed against the drum (5), driven at constant speed by a motor.

Owing to the damping in the rubber the compressive stresses in the right and left halves of the area of contact between the rubber and the drum are unequal; this sets up a torque reaction in the driving shaft (6), which is measured by the swing of the motor-gearbox system (suspended on ball races) away from the vertical.

The measurements made are (i) the vertical deflection (compression) of the rubber, d; (ii) the torque T on the shaft (6). Then:

$$E^* = Fh/sbk_n d^{3/2}\sqrt{r} \tag{6}$$

where E^* = complex Young's modulus corresponding to strain amplitude d/h

- F = force acting on test piece
- h = radial thickness of test piece
- d = vertical deflection
- b = width of text piece
- s = shape function† (normally about 1·3 for the type of wheel used; determined by comparing E^* from equation (6) with direct measurements)
- r = outer radius of test piece and of drum
- k_n = function of n (see Table 6)

where n = a numerical factor expressing the non-linearity of the stress/strain curve, i.e. stress proportional to (strain) $^{1-n}$.

The deformation of the test piece corresponds to half a dynamic cycle, and the resilience R, or ratio of energy output to input, during one revolution is given by:

$$\sqrt{R} = -(L/2W) + \sqrt{1 + (L/2W)^2} \tag{7}$$

where L = energy loss per revolution = $2\pi T$

- W = work stored in test piece at maximum compression = $C_n F\sqrt{d}$ Joules, C_n being a function of n (see Table 6)
- T = torque.

Since, other things being equal‡, F is proportional to $d^{3/2-n}$ a series of tests with varying loads and hence d, enables n to be determined by plotting

† See footnote on page 13.

‡ This implies, in equation (6), replacing E^* by $E^*_0(d/hA_0)^{-n}$ (cf. Appendix A); since E^*_0 is a constant, this makes F proportional to $d^{3/2-n}$.

log F against log d; E^* can then be evaluated from equation (6) and R from equation (7). Tan δ is then given by:

$$\text{Tan } \delta = -\frac{1}{\pi} lnR$$

E' and E'' are then obtained from equations analogous to (4). The energy loss *per cycle*, as defined in Clause 2.9, equals $2L$.

This apparatus gives (compression) strain amplitudes between 5 per cent and 25 per cent, and equivalent frequencies from 10 to 200 c/s. Temperature is controlled by an oven surrounding the test piece, giving a range from 20°C up to 200°C.

The machine can measure values of modulus (E') from 15 kgf/cm² to 150 kgf/cm², both at 10 per cent strain, with extensions down to 5 kgf/cm² at 25 per cent strain and up to 450 kgf/cm² at 5 per cent strain, and values of loss tangent from 0·012 to 0·7.

TABLE 6. VALUES OF CONSTANTS IN EQUATIONS (6) AND (7)

n	k_n	C_n (for values of F in kgf and d in mm)
0	1·333	0·165
0·1	1·372	0·168
0·2	1·416	0·172
0·25	1·440	0·174
0·3	1·464	0·176
0·4	1·512	0·181
0·5	1·570	0·186
0·6	1·636	0·192
0·7	1·714	0·197
0·75	1·750	0·201
0·8	1·792	0·204
0·9	1·884	0·212
1·0	2·000	0·220

III. TRANSDUCER MACHINE

Sinusoidal force cycles are produced by an electromagnet fed with alternating current of appropriate frequency. These cycles are transmitted to rubber test piece(s) of such form, and so mounted, as to produce stress cycles in shear, deformation or otherwise as required. Figs. 9*a* and *b* show suitable arrangements for tests in compression (Ref. 3) and Fig. 9*c* for tests in shear (Ref. 2).

In the compression apparatus the required mean initial stress is applied to the test pieces 1 and 2 by compression of the calibrated spring 3, after which plate 4 is locked in position, thus maintaining the mean strain. Force cycles generated in coils 5 are transmitted to the test pieces by the moving member 7. The applied force amplitude F is calculated from the driving current, I, and the coil characteristics. The amplitude of deformation produced by this force is determined by the coils 6, which are velocity detectors. This amplitude d is calculated from the coil characteristics, applied frequency, and detected voltage V.

If tests are carried out under conditions such that the mass reactance $m\omega^2$ of the moving system is not negligible compared with the stiffness reactance of the test pieces, or the coil support stiffness and damping are not negligible, then appropriate corrections should be made.

The coil systems are suspended by eight spring steel ligaments, 0·005 in (0·12 mm) thick, 0·38 in (10 mm) wide, 2 in (50 mm) long.

The required calibration constants, and methods of determination, are as follows:

1. m, the mass of the vibrating parts, found by direct weighing,

2. P, the force per unit current for all the coils, found by measurements, with no test piece in place, of

either (i) the d.c. current required to support added masses, when the coil/magnet assemblies are vertical,

or (ii) the vibration amplitude (α), measured e.g. by a microscope, of the vibrating parts (mass m) with a known alternating current (c) of frequency v (c/s); whence

$$P = \frac{4\pi^2 v^2 \alpha m}{c}$$

provided the natural frequency of the vibrating parts is low compared with v. If m is not known, readings of the supporting current, or the vibration amplitude α can be taken with known added masses, when m and P can be readily deduced (Ref. 3).

3. K, the voltage per unit velocity for the detector coils, calculated from $K = 10^{-7} P$ (with K in volts.cm^{-1} sec and P in dynes.amp^{-1}).

4. S_0 and D_0, the stiffness and damping of the coil suspensions, measured by an experiment with no test piece.

Experimentally, the force amplitude on the test piece is given by $F = P \times I$, and the deformation amplitude by $d = \frac{V}{2\pi f.K}$ where f = frequency, c/s.

Hence, the stiffness S, given by F/d, can be calculated.

The loss angle δ is determined from the relative displacement of the sinusoidal traces, on a cathode ray tube, produced by the driving current and the *integrated* voltage from the pickup coils.

These values must be corrected by S_0 and D_0 if necessary.

Alternatively, by the use of a co-ordinate potentiometer, the stiffness and tan δ can be determined directly in terms of a resistance and a mutual inductance.

To deduce the complex modulus G^* and its in-phase and out-of-phase components G' and G'', the stress amplitude Σ and strain amplitude Δ are calculated from the corrected values of F, d, and the test piece dimensions and these values used in equation 1, 2A, or 3A as appropriate, and equation 4.

Transducer apparatus is applicable to rubbers with any value of loss angle.

Test frequencies range from 1 to 400 c/s in the compression apparatus described, and 20 to 5000 c/s in the shear apparatus.

The small compression apparatus (Fig. 9*b*) produces force cycles up to 2·72 lbf (1·2 kgf) r.m.s., and measures stiffnesses up to 20 000 lbf/in (3500 kgf/cm).

The deformation amplitudes attainable are small, e.g. maximum of 0·05 in (1·2 mm) in the compression apparatus.

The range of operating temperatures is limited by the choice of materials (e.g. for the driving and pick-up coils) capable of working at elevated temperatures.

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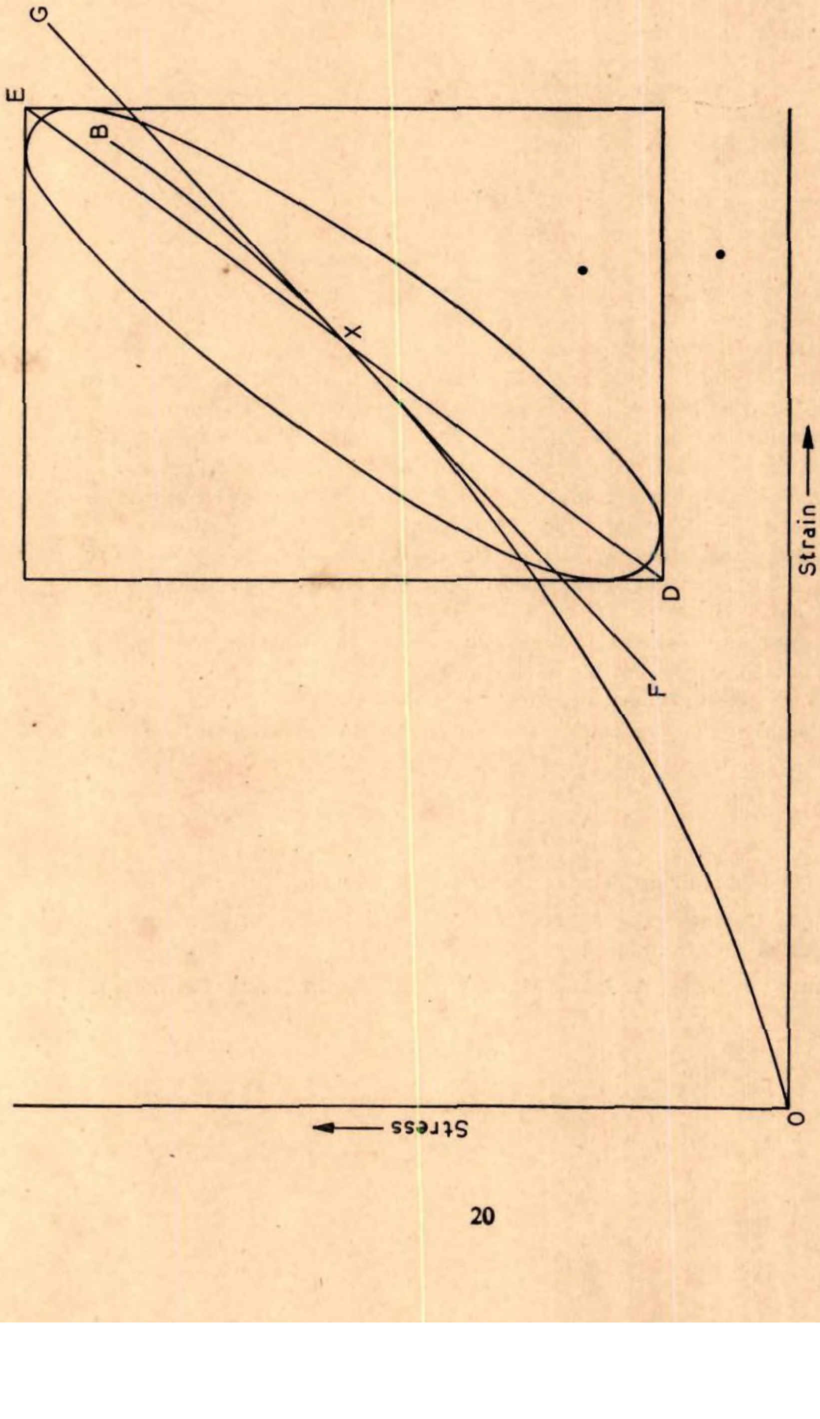


Fig. 1. Hysteresis loop in dynamic stress/strain cycles

OXB = ' static ' stress/strain curve; FG = mean modulus at X; DE = complex modulus

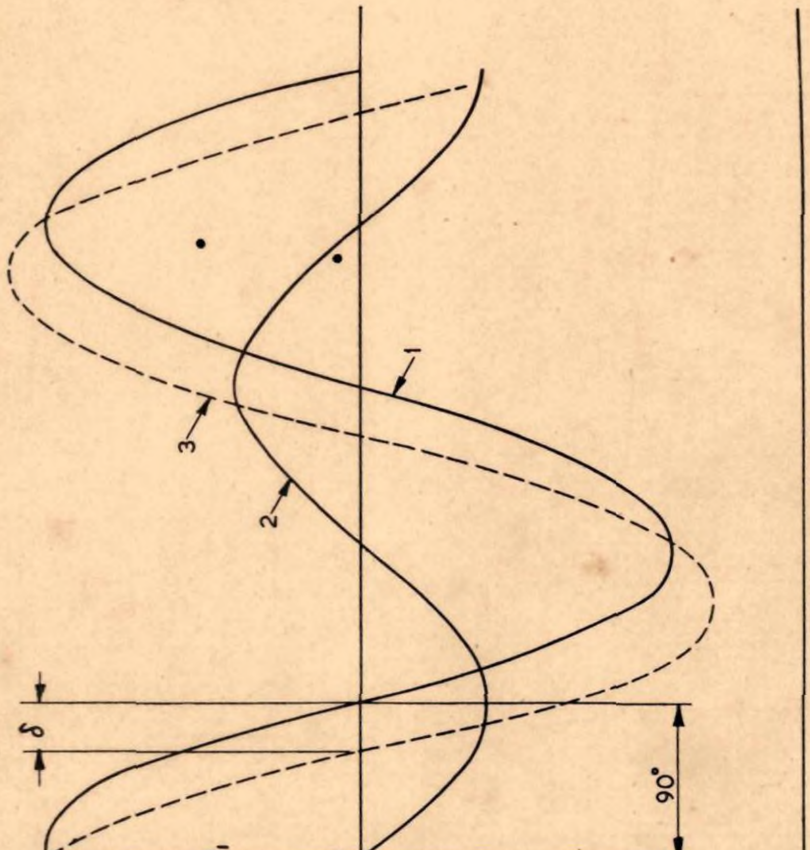


Fig. 2. Sinusoidal stress cycles

1: In-phase; 2: out-of-phase; 3: resultant (total), displaced by loss angle δ

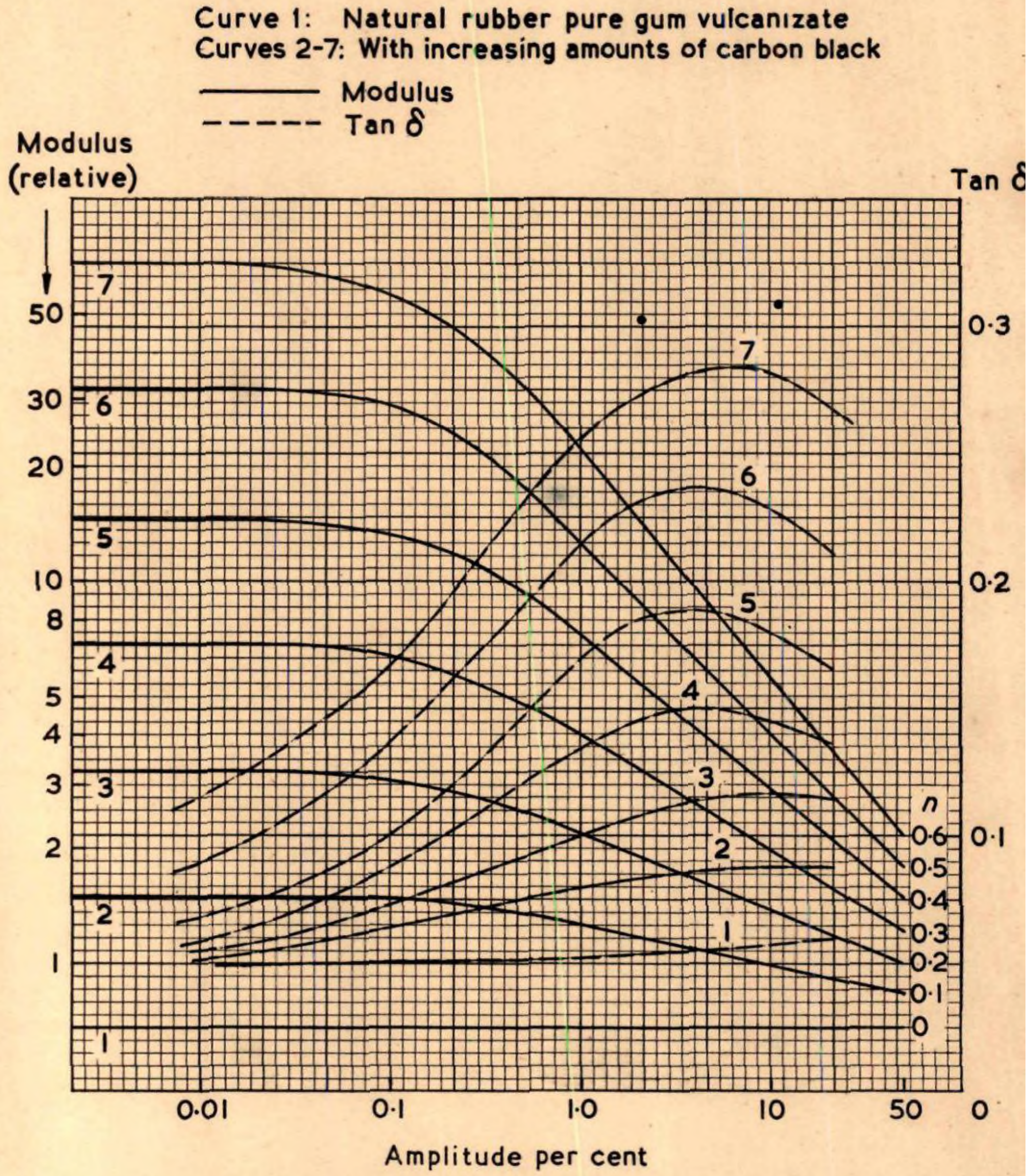


Fig. 3. Variation of complex modulus and tan δ with amplitude of strain cycles

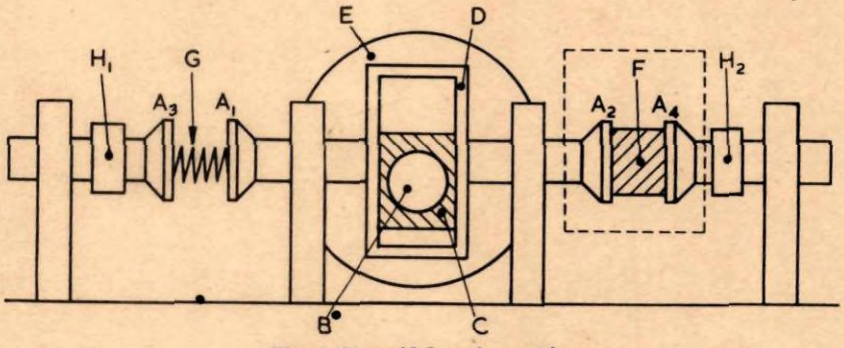


Fig. 4. Sinusoidal strain machine

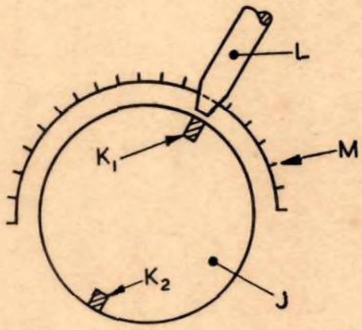


Fig. 5. Device for measuring loss angle (sinusoidal strain machine)

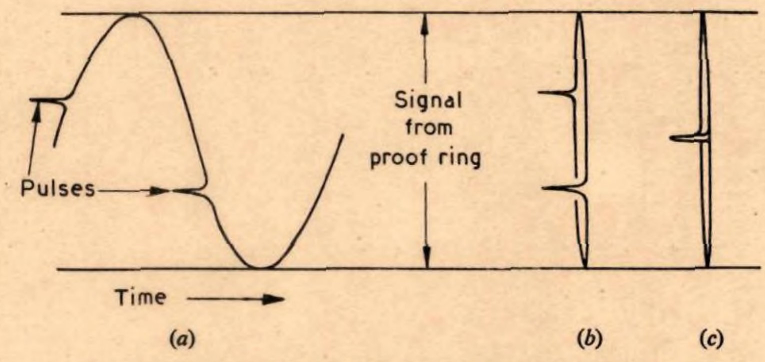


Fig. 6. Principle of loss angle measurement (sinusoidal strain machine)

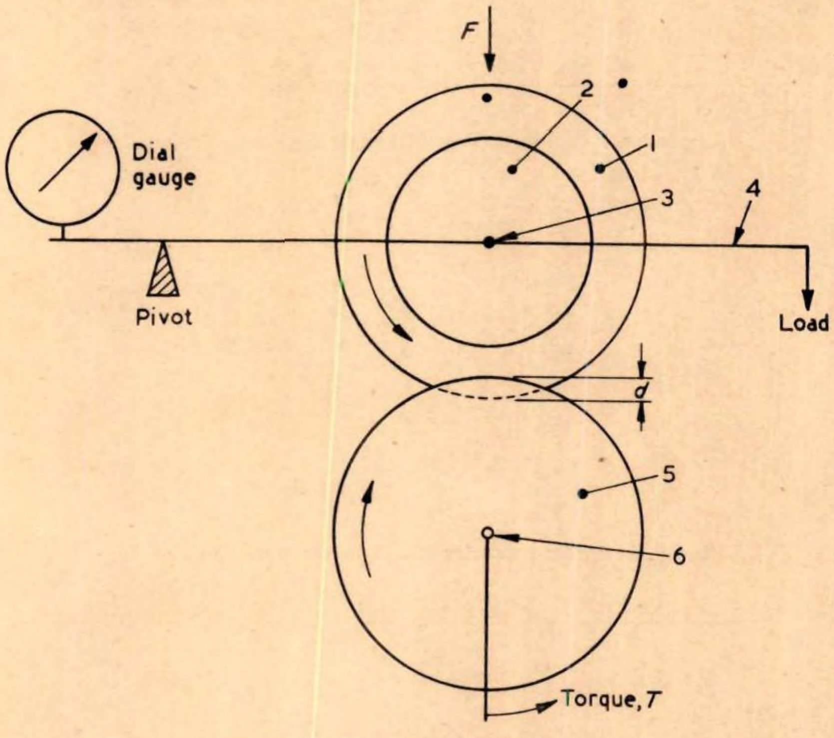
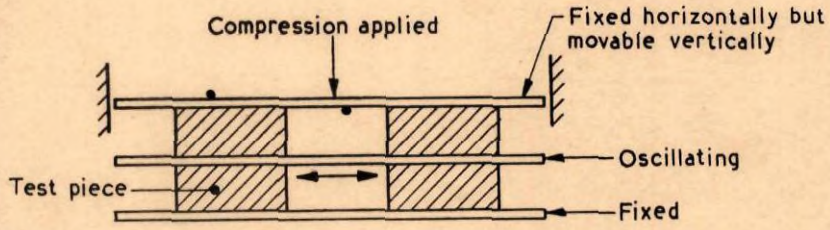
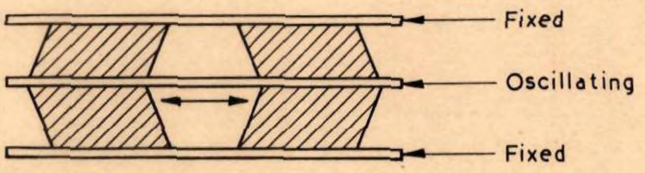


Fig. 7. Rotary power loss machine

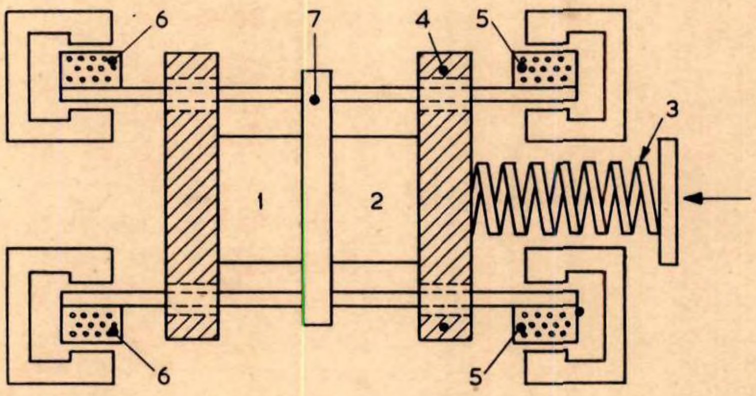


Tests with pre-compression

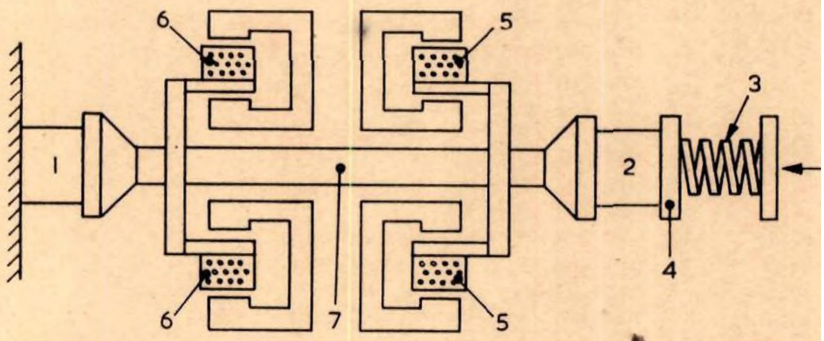


Tests with pre-shear

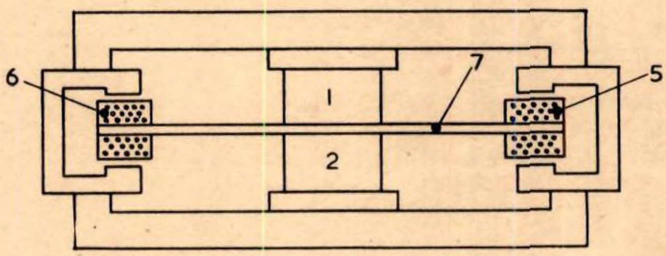
Fig. 8. Arrangement of shear test pieces



a.



b.



c.

Fig. 9. Transducer apparatus

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