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USE OF FILLED RUBBER FOR ISOLATION OF NOISE AND VIBRATION

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1. INTRODUCTION

Rubber springs are frequently used as compliant elements to reduce vibration transmission. In some cases the source of the vibration is isolated; engine mounts are used for this purpose, Ahmadi & Muhr [1]; in other cases the receiver is isolated: many buildings near railway lines have been built on laminated rubber bearings, Coveney, et al. [2].

The specification of a vibration isolation spring invariably includes its dynamic stiffness and, increasingly, its damping. System performance may then be calculated either in terms of a resonance curve for a simple system or in terms of the four-pole parameter formalism, Snowdon [3], Ahmadi & Muhr [1], for a compound system (intermediate mass or compliant foundation).

At frequencies in the upper audio range wave effects within a mount, and so material density, may become significant: springs containing rubber elements are particularly effective at reducing transmitted vibrations in such circumstances, Muhr [4]. Rubber isolation mounts offer attractions in terms of cost, simplicity, reliability and compactness when used either in rubber-only systems or in conjunction with other systems including active control. Elastomers thus already fulfill an invaluable role, however if they are to be used to maximum effect in vibration isolation their dynamic properties need to be well understood.

2. BASIC DYNAMIC PROPERTIES OF RUBBER

The dynamic modulus and damping properties of rubber are often represented by combinations of Hookean spring and viscous damping elements, Thomson [5]. Although such representations make for convenient analysis they have limitations when compared with the behaviour of real rubbery materials. The damping in practical elastomeric materials is produced by a number of mechanisms but viscous processes are rarely predominant. As a result, the loss factor ($\tan\delta$) and the complex modulus (G^*) of rubber does not generally increase linearly with frequency - in many cases the dependence is weaker, Ahmadi & Muhr [1] and Gregory [6]. For natural rubber operating at moderate temperatures and frequencies an increase in complex modulus of 10% per two decades increase in rate of deformation is an order-of-magnitude guide to the frequency dependence of the material; the dependence of loss factor on frequency is of a similar order.

Most practical elastomers for engineering applications are filled - often with fine particles of carbon (carbon black); the reasons for this range from advantages in processing characteristics through improvements in fatigue resistance to enhancement of damping. Significant carbon black reinforcement is less essential for natural rubber than for most of the synthetics on strength grounds. Nevertheless carbon-black filler is the rule for natural as well as synthetic rubber. For natural rubber, vulcanizates, and for other elastomers with intrinsic low damping at moderate temperatures and frequencies, much of the damping is associated with the carbon-black filler.

Whereas unfilled natural rubber deformed in shear exhibits an essentially linear force-deflection characteristic up to several hundreds of percent strain, the shear modulus of black-filled rubber is stiffer both at low and at high strains than at moderate strains. An extreme example of this effect is shown in Fig 1; the quasi-static force-deflection behaviour is shown for an unfilled natural rubber vulcanizate and one filled with 75 parts (by weight per 100 of rubber) reinforcing carbon black. The low strain stiffness in black-filled vulcanizates is believed to be due to interactions between carbon black particles, and that at high strains due to carbon black rubber network interactions. When filled rubber is subjected to sinusoidal displacement histories in shear, related phenomena are observed. The modulus at low strain amplitudes (less than 0.1) is higher than at moderate to high strains. There is a progressive increase in modulus as strain decreases down to $\sim$ .001; at these strain levels a plateau in modulus is reached.

The behaviour of the loss factor is to increase for decreasing strain amplitudes below 1.0; a maximum in loss factor is reached at strain amplitudes $\sim$ .05. Plots of shear modulus against shear strain amplitude are shown in Fig 2 for a range of natural rubber vulcanizates with different filler loadings.

At the larger strain amplitudes in particular the force-deflection loops depart noticeably from elliptical shapes - indicating the presence of higher harmonics in the force-time signal, Fig 3. At lower strains higher harmonics occur wherever there is significant filler-induced damping.

In addition to the foregoing effects, the behaviour of filled rubber is history dependent.

3. HISTORY-DEPENDENT BEHAVIOUR - BACKGROUND

It has been recognized for many years that when carbon-black filled rubber is subjected to cyclic shear strain it becomes softer, Payne [7]. In most cases this softening is reversible; recovery from the effects of large strain cycling can be monitored by subjecting the testpiece to small strain cycling and measuring the changing stiffness, Fletcher & Gent [8], Coveney & Ahmadi [9]. The data suggest that immediately after large strain cycling the small strain modulus is depressed to a value close to the large strain modulus (see Fig 4).

Recent experiments reported by Harris [10] have implied that a filled rubber, normally thought highly nonlinear, can, when subjected to certain complex displacement histories, behave as if it were linear with a modulus close to that appropriate to the peak strain. Yet for sinusoidal deformations of different strain amplitudes, and also for a static strain superposed on a dynamic strain, nonlinear behaviour occurs with the stiffness being lower for larger strains, Coveney & Ahmadi [9], Gregory [6].

The current work on filled vulcanizates is directed towards studying the boundary between conditions for which there is nonlinear behaviour and those for which linear behaviour occurs for filled rubbers.

4. CURRENT STUDY OF HISTORY-DEPENDENT BEHAVIOUR

A range of types of strain histories were applied to a test piece of natural rubber filled with 75 parts (per hundred by weight of rubber) of N330 (reinforcing) carbon black. This material was chosen as an extreme example to maximize nonlinear effects. The test piece was the standard cylindrical double shear, with a rubber diameter of 25mm and thickness of 6mm per side.

A Schenck VH7 servohydraulic machine which has a wide frequency capability (0.1 to 800Hz) was used to perform the tests. Command signals and preliminary analysis of the data were provided by a Schlumberger Solartron frequency response analyser 1250 and fast fourier transform analyser (FFT) 1201. All tests were performed at room temperature (23°C) unless otherwise stated.

4.1 Sequential sine-sine

Initial tests were performed on rested rubber in which the testpiece was subjected to large strain amplitude ($\sim$ 0.5) cycles at 1Hz followed by small strain cycles (0.003) at 1 & 10Hz. The experiments were performed at -30°C and room temperature (23°C). The results of the tests were consistent with the hypothesis that the stiffness at small strains immediately after cessation of large strain cycling is equal to the large strain stiffness; the data suggested that very rapid recovery in stiffness occurred in the first 1s, with recovery rate becoming more rapid at higher temperatures. Recovery behaviour at shorter times was not observed because of the settling time of the servohydraulic machine.

4.2 Superimposed sine-sine

Experiments were carried out along the lines of those previously reported, Harris [10]. A rested testpiece was used. In one set of tests 95Hz sinusoidal deformations with strain amplitudes from 0.001 to 0.1 (primary signal) were combined with simultaneous sinusoidal deformations of 0.1 strain amplitude and frequencies ranging from 1 to 50Hz (secondary signal). The resulting force signals were then analysed for the primary frequency components and an apparent primary signal modulus (G_a) deduced. As compared with the case of a primary strain-time signal without a secondary present, G_a at small strains is progressively softened as the secondary frequency is increased. In a second set of tests the primary signal had a fixed frequency of 10Hz and its strain amplitude was varied from 0.01 to 0.1 while the secondary signal had a fixed frequency of 1Hz and its strain amplitude was varied from 0.1 to 0.5. As compared with a primary signal without a secondary, the apparent primary signal modulus at small strains was progressively softened as the secondary strain amplitude was increased. The results confirmed those of Harris [10]; for a primary signal whose frequency is within a factor of two or so of the secondary's frequency the apparent modulus for the primary signal is largely linear for a wide range of strains below the strain amplitude of the secondary signal.

These results were interpreted by Harris in terms of large strains causing softening and the number of strain reversals (of the primary signal occurring in one secondary cycle) increasing the extent of recovery of small strain stiffness.

4.3 Pseudo-random signal

The maximum voltage associated with any pseudo-random signal produced by the Solartron 1201 is around 3.7 times the average r.m.s. value. An example of a typical near-Gaussian distribution of (average) strain values at 5ms intervals produced by the FFT during a 2.97s period is shown in Fig 5. A range of such signals were used to drive the servohydraulic machine - along similar lines to previously reported experiments, Harris [10]. In each case the frequency band was 40-140Hz. One factor which complicates precise analysis of such tests is the gain of the servohydraulic machine being a (decreasing) function of frequency; it is unity at approximately 80Hz.

It was found that the 80Hz dynamic stiffnesses derived from the pseudo-random tests were significantly lower than stiffnesses obtained from the same fully rested testpiece subjected to sinusoidal deformation at 80Hz and strain amplitudes equal to the peak random signal amplitudes (PRSA). Excellent correlation was, however, obtained between the pseudo-random stiffnesses and those obtained from sinusoidal tests at amplitudes of half PRSA (Table 1).

4.4 Pseudo-random superimposed on sine

These experiments were performed in order to discover whether effects similar to those observed for superposed sinusoidal strains occurred. The stiffnesses of a fully rested rubber shear testpiece at 80Hz for pseudo-random deformations (primary) with a frequency band of 40-140Hz were measured with and without a superposed sinusoidal signal (secondary: amplitude 0.1, frequency 1Hz and amplitude 0.5, frequency 1Hz). In spite of the large ratio between the secondary and primary signal frequencies the presence of the secondary caused a very significant reduction in the dynamic stiffness associated with the primary signal (see Table 2). In effect, the primary response had become more linear. The primary stiffness was reduced by up to 60% towards the dynamic stiffness associated with the secondary - the effect being proportionately larger for low primary (pseudo-random) signals and high secondary (sinusoidal) signals. As was the case for the sine-sine conditions, the presence of the secondary increased the loss angle associated with the primary.

5. MATERIAL NONLINEARITY AND MOUNT DESIGN

Elastomeric vibration isolation mounts are made in a wide variety of shapes and sizes. In many there is little alternative to using trial-and-error or finite element methods. In others there are analytical design methods available; laminated rubber bearings used for vibration isolation in buildings are one such class. The overall compressive compliance of such a bearing is obtained by adding the compliances of individual layers. For a bearing of compact (eg. circular or square) plan area A, the compressive stiffness of an individual rubber layer of thickness h is given by

$$k_c = \frac{6AGS^2}{h} \qquad (1)$$

where S, the shape factor, is defined as the ratio of a single loaded area to the unloaded (side) area of a single rubber layer. Equation (1) assumes moderate shape factors and strictly applies only to a linear rubber of shear modulus G and for small strains. However, a measure of the level of equivalent shear strain ($\bar{\gamma}$) in the rubber due to a compressive strain (e_c) is given by: Muhr et al. [11].

$$\bar{\gamma} = \sqrt{6}\, S e_c \qquad (2)$$

For a nonlinear material an appropriate value for G may therefore be substituted into equation (1). (Equations (1) and (2) are simplifications of more general formulae given in [11]). Comparisons between experimental values and the predictions of equations (1) and (2) are shown in Fig 6. Good agreement is indicated for compressive strain levels of 0.08 and less.

6. DISCUSSION/CONCLUSIONS

The term "dynamic to static ratio" is often used in relation to the stiffness of elastomeric vibration isolation mounts. Clearly any difference in stiffness will affect the vibration transmission characteristics of a mount; the difference between stiffness measured for relatively large quasi-static and small dynamic displacements arises from two separate sources. The first source relates to genuine frequency dependence in material properties; modulus can exhibit strong frequency dependence for some elastomers (nitrile and epoxidized natural rubbers being two examples) however other elastomers (such as unmodified natural rubber and polybutadiene) show little frequency effect at moderate temperatures and frequencies. For filled unmodified natural rubber the main source of "dynamic to static ratio" lies not in a genuine frequency effect but in the difference between strains during the static test and the dynamic application. Indeed for high frequency applications dynamic strains may be sufficiently small for the filled rubber to be operating in its low-strain plateau region; if this is the case the material will behave linearly. A degree of linearity may also be achieved for certain complex waveforms, current work has added to known members of this class although the range of waveforms to which this statement applies has yet to be fully quantified. Progress has likewise been achieved over recent years in accounting for material nonlinearity in the design of filled rubber isolation mounts of certain geometries; these techniques now need to be extended to more complex geometries.

7. REFERENCES

[1] H R AHMADI & A H MUHR, 'Vibration Control using Rubber Components IAVD March (1991). (To be published).

[2] V A COVENEY, C J DERHAM, K N G FULLER & A G THOMAS, 'Vibration isolation and earthquake protection of buildings', p.938 Natural Rubber Science and Technology, A D ROBERTS ed. Oxford University Press (1988).

[3] J C SNOWDON "Vibration isolation: Use and characterization" U.S. Department of Commerce/National Bureau of standards Handbook 128. (1979).

[4] A H MUHR, 'Transmission of noise through Rubber-Metal composite springs' Proc. Institute of Acoustics Vol.11, p.627 (1988).

[5] W T THOMSON, 'Theory of Vibration with applications' Prentice Hall 3rd Ed. (1988).

[6] M J GREGORY, 'Measurement of rubber properties for design' Polymer Testing, vol. 4, p.211, (1984).

[7] A R PAYNE, "Strainwork dependence of filler-loaded vulcanizates" British Society of Rheology Conference, Shrivenham, 9-12 Sept. (1968).

[8] W P FLETCHER & A N GENT, "Non-linearity in the dynamic properties of vulcanized rubber compounds". Trans. IRI, Vol. 29, p.266 (1953).

[9] V A COVENEY & H R AHMADI, "Non-linearity in High-damping natural rubber bearings for Seismic Isolation", Proc. International Symposium on Pressure Vessel Technology and Nuclear Codes and Standards, Seoul, 19-21 April (1989).

[10] J A HARRIS, "Dynamic testing under nonsinusoidal conditions and the consequences of nonlinearity for service performance", American Chemical Society, May 26-29, (1987).

[11] A H MUHR, G H TAN & A G THOMAS, "A method of allowing for non-linearity of filled rubber in force-deformation calculations". Journal of Natural Rubber Reseach, Vol. 3, No 4, p.261. (1989).

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PRSA	PRBS G^* & δ' at ∿ 80Hz		Sine wave @ PRSA and ∿ 80Hz		equivalent sine wave strain for same G^* of PRBS (rested)
	G^*	δ'	G^*	δ'	
0.01	8.20	9.40	6.96	11.35	0.0047
0.02	6.88	11.80	5.66	12.94	0.0096
0.05	5.06	12.90	4.12	12.48	0.0262
0.07	4.60	13.00	3.77	11.65	0.0358
0.10	4.16	12.30	3.37	10.57	0.0492

Table 1 : Correlation between PRBS and single Sine wave tests.

(a) Sine wave (secondary) 1Hz at 0.1 $G^* = 3.02$ $\delta' = 9.68$

PRSA	PRBS only @ ∿ 80Hz		PRBS + Sine @ ∿ 80Hz	
	G^*	δ'	G^*	δ'
0.01	8.2	9.40	6.06	16.5
0.02	6.88	11.80	5.42	15.6
0.05	5.06	12.90	4.58	14.4
0.07	4.6	13.00	4.24	14.6
0.10	4.16	12.30	3.95	14.1

(b) Sine wave (secondary) 1Hz at 0.5 $G^* = 2.00$ $\delta' = 8.42$

0.01	8.2	9.40	4.48	22.3
0.02	6.88	11.80	4.30	21.3
0.05	5.06	12.90	4.07	18.7
0.07	4.6	13.00	3.90	18.6
0.10	4.16	12.30	3.62	16.8

Table 2 : Secondary sine wave affect on Primary PRBS Dynamic Properties.

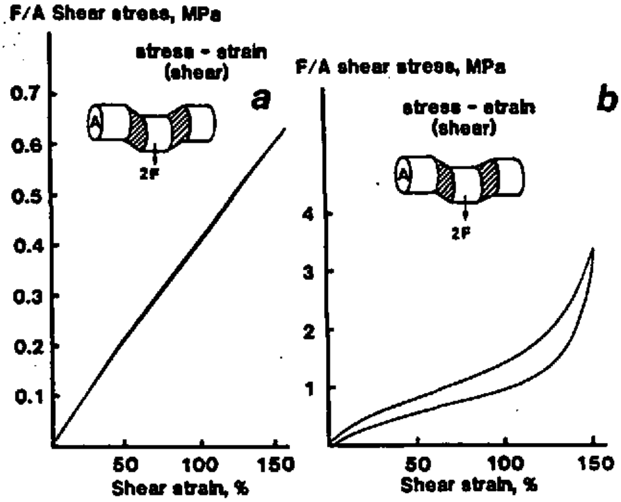

Figure 1. Quasistatic deformation in shear for
(a) Unfilled natural rubber
(b) Natural rubber filled with 75phr N330 black

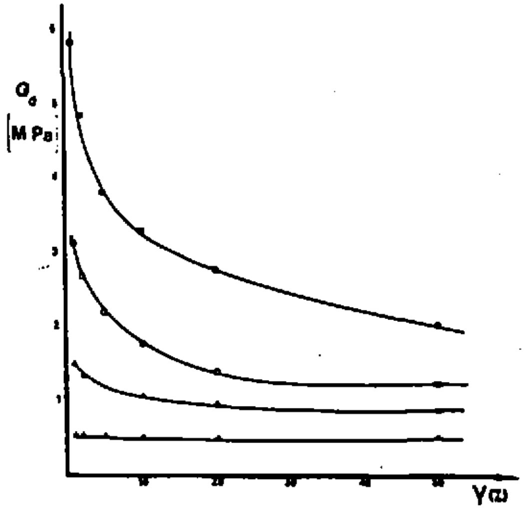

Figure 2. Shear modulus against shear strain amplitude for various filler loadings. ■ 75pphr N330,□45,▲30,△Gum Rubber.

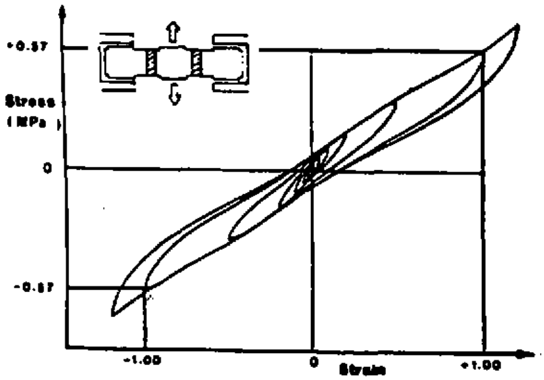

Figure 3. Shear stress strain curves for a high damping natural rubber earthquake vulcanizate. (0.5Hz sinusoidal input).

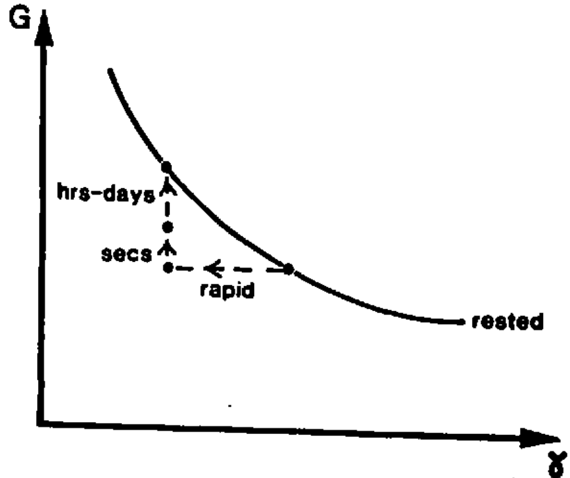

Figure 4. Filler-induced non-linearity: breakdown and recovery according to Fletcher and Gent hypothesis. (G is shear modulus γ shear strain amplitude).

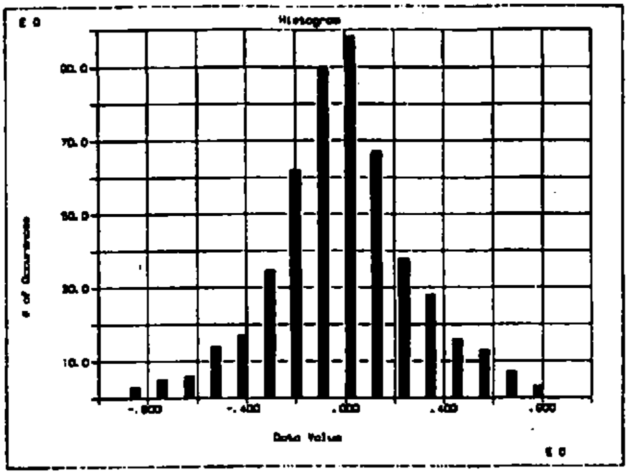

Figure 5. Distribution of strain levels: pseudorandom input.

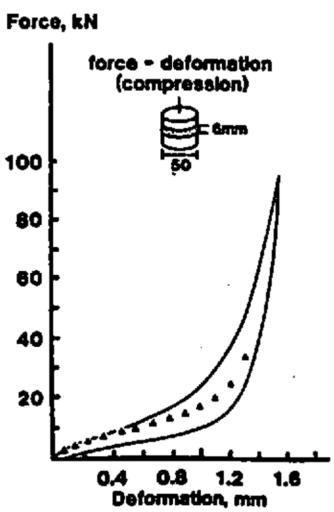

Figure 6. Quasistatic deformation of natural rubber plus 75phr N330: compression.