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(6) CONTRIBUTIONS OF THE MART PROGRAM TO
MATH MODELING AND MATERIAL CHARACTERIZATION
OF ELASTOMERS FOR TRANSDUCER APPLICATIONS

by

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Letter on file

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Summary

Under the MART Program, General Dynamics/Electric Boat Division has conducted studies to determine the properties of rubber materials that are of interest in sonar application. These properties were used in math models to predict the behavior of these rubber materials in sonar applications such as head mount or tail mount configurations. The math models for the rubber components were used in composite math models for transducer elements. Some of the highlights of the rubber materials work performed by EB are given below:

(1) Established the Rheovibron testing method and the Time-Temperature Superposition Principle as a means of determining Young's modulus and loss factor as a function of frequency and temperature.

(2) Ran tests and obtained permeation rates of water and filler gases through isolation mount materials of existing transducers.

(3) Developed a math model to predict loss of filler gas for the 3C5, BQS-6C and TR208 elements so that transducer service life predictions could be made.

(4) Developed math models for rubber head and tail mounts so that interstitial effects could be included in array performance predictions.

(5) Developed a replacement material for the head mount of the TR-155D so that temperature variations would not have such a drastic effect on element performance.

Based on the work discussed above EB has made the following recommendations concerning rubber materials for use in sonar applications.

(1) EPDM based isolation compounds appear to exhibit a better balance of dynamic and environmental properties than other types of elastomers.

(2) When isolation properties (low damping and stiffness) are of primary importance, polybutadiene gum stocks and possibly silicones are preferable to the general purpose EPDM formulations.

Introduction

Under the MART Program, General Dynamics/Electric Boat Division (EB) has conducted various studies to determine the effects of rubber materials in sonar systems. These studies have shown that the rubber materials strongly influence the performance of sonar systems. EB has shown that in a performance analysis of any of the existing arrays interstice impedance must be modeled if meaningful and reliable results are to be obtained. Since rubber materials are contained in the interstices, a knowledge of the dynamic properties of elastomers is required for a performance analysis of sonar arrays.

Element failures that have occurred in the past might have been avoided if careful consideration had been given to the environmental, permeation, and dynamic properties of the elastomer used in the element.

In selecting a rubber material for a particular sonar application trade-offs between dynamic, permeation, and environmental properties are involved. EB has conducted studies to determine dynamic and permeation properties of various elastomers. Using this data and mathematical models of various degrees of sophistication, attempts have been made to find optimum elastomers for various sonar applications.

This report will review the work performed by EB in the area of rubber materials under the MART Program. This report is intended to be a time saving aid to the sonar scientist or engineer who is concerned with the applications of rubber materials in sonar systems. The rubber modeling work is documented in various monographs and informal reports issued over a two year period under the MART Program. Experience has shown that it is difficult and time consuming to use these source documents on rubber modeling technology. Therefore, this report gives a brief description of the rubber modeling work performed under the MART Program and cites specific references where a detailed discussion can be found.

For the work that EB performed under the MART Program the program manager was G. Moore, NAVSHIPS Code 9012 and the overall technical director was D. Carson, NUC Code 60101.

Desirable Properties of Elastomers

The particular application for which the elastomer is being used determines the properties of the elastomer which will be most important. For example, in a boot material the permeation properties of the elastomer would be of paramount importance, but in a head mount application the dynamic properties would also be very important.

In attempting to choose an elastomer for a particular sonar application the following properties are important:

(1) Ability to withstand the physical and chemical stresses which occur at the face of a sonar array (tear, abrasion, cavitation, water, oil, etc.) or in drydock (oxygen, ozone, sunlight);

(2) Long term reliability which encompasses gas and water permeability and bond strength in the environment;

(3) Processing cost and availability;

(4) Array performance where it is desirable to have low damping, high bulk modulus and the ability to obtain a constant shear modulus over the temperatures and frequencies encountered in operation.

Before the work performed by EB under the MART Program information on the properties mentioned above was limited or non-existent for most elastomers. Through the work done under the MART Program, the properties of various elastomers have been investigated. The main areas of emphasis have been the dynamic properties and the permeability of elastomers.

Material Parameters of Elastomers

As was mentioned in the previous section, the dynamic properties and permeability of elastomers have been investigated under the MART Program. The majority of the work performed by EB has been in the determination of the dynamic properties of rubber materials. Various methods of obtaining these dynamic properties have been implemented and a discussion of these methods will be presented in the next section.

The term incompressible is often applied to rubber materials because the Poisson's ratio, σ, for such materials is very nearly equal to 1/2. The usual moduli of elasticity (shear, bulk, Young's) become complex in the case of rubber materials. Since the Poisson's ratio is nearly 1/2, the relationship between the complex shear modulus G^* and the complex Young's modulus E^* for a rubber material is approximately $E^* = 3G^*$.

An additional characteristic of the complex modulus is that the modulus is a function of frequency and temperature. The frequency dependence of the complex modulus of an elastomer is an important property that must be considered when the elastomer is to be a component of a sonar system.

A knowledge of the complex shear or Young's modulus and the complex bulk modulus or Poisson's ratio as a function of frequency and temperature is required to completely determine the dynamic properties of a rubber material. Under the MART Program, a systematic attempt to include the frequency-temperature dependence of the complex modulus for rubber materials in the design and analysis of sonar systems was undertaken.

A general idea of these frequency-temperature effects on the complex modulus can be seen in Figure 1 and Figure 2. The complex Young's modulus, E^*, is written as $E^* = E(1 + i \tan \delta)$ where E is the real part of the Young's modulus and $\tan \delta$ is the loss factor. The loss factor is given as the ratio of the imaginary part of the Young's modulus to the real part.

The curves of modulus and loss factor vs frequency can essentially be divided into three regions. This is shown in Figure 3. The first region denoted as the elastic region is characterized by a small loss factor and a modulus of approximately 10^6 - 10^8 dynes/cm^2. In the transition region the modulus increases rapidly with frequency and the loss factor assumes its maximum value.

In the glassy region the material may become brittle as the modulus approaches a constant value of approximately 10^{10}dynes/cm^2 and the loss factor decreases. The figures that have been presented in this section were taken from Reference 1.

The high (low) frequency behavior of the modulus and loss factor is the same as the low (high) temperature behavior. This relationship between frequency and temperature will be investigated in the next section when the Time-Temperature Superposition Principle is discussed.

In Reference 1 a brief discussion is given describing how the dynamic properties of rubber materials can be modified by vulcanization and the addition of fillers and process oils.

In an attempt to find a rubber material which would best satisfy the requirements for sonar applications, EB formulated ten rubber compounds to obtain various properties which are related to acoustic performance[2]. . These ten rubber blends that were investigated comprise five different polymers: neoprene, ethylene-propylene, buna N, epichlorohydrin, and natural rubber. These blends were compounded in order to obtain a parametric study of rubber mount and interstice materials.

Another property that is important in sonar applications of rubber is permeability to both water and gases. The permeation properties of the rubber components influence the long term reliability of sonar systems.

Gas permeability through a polymeric material is a three-step process: absorption of the gas into the material, diffusion through the mount, and desorption at the outside surface[1]. Gas permeability is an important consideration because loss of filler gas through the front isolation mount has been reported to be responsible for element failures in the past[3].

As a first step in obtaining permeation rates, gas transmission tests were conducted by EB using Freon C-318 (C_4F_8), sulfur hexafluoride (SF_6) and nitrogen[4]. Three mount materials were tested: the neoprene compound used in Raytheon's BQS-6C element, a polybutadiene similar to that used in Massa's TR208A element, and the EPDM compound presently used in the 3C5 element.

Water permeation is another possible cause of element failure so water permeation tests were conducted at 40°F, 73°F, and 100°F for the three mount materials mentioned in the previous paragraph.

EB developed a math model for estimating the service life of an element by calculating the rate of gas loss for each of the mounts mentioned above. They found that all combinations of the filler gases (SF_6, Freon C-318, and nitrogen) and elastomers (neoprene, polybutadiene, and EPDM) which were tested are acceptable for use in the three elements as far as gas loss rate is concerned.

The material with the highest free volume (polybutadiene) exhibited the highest water vapor transmission rates. By going to a nonpolar, saturated material (EPDM), water vapor transmission rate was substantially reduced even though this material also has the high polymer chain mobility required for good isolation properties. These water vapor transmission tests were performed with fresh water.

In a recent investigation [5] the task assigned to EB was to find a replacement for the mount material of the TR-155D. The replacement material was to be chosen so that its dynamic properties were as insensitive to temperature and frequency as possible. The permeability properties of the replacement material also had to be considered. As a result of the TR-155D investigation EB has come to the following conclusions:

(1) EPDM based isolation compounds appear to exhibit a better balance of dynamic and environmental properties than other types of elastomers;

(2) When isolation properties (low damping and stiffness) are of primary importance, polybutadiene gum sticks and possibly silicones are preferable to the general purpose EPDM formulations.

Methods of Obtaining Dynamic Properties

One of the major efforts by EB in the area of rubber materials has been obtaining the dynamic properties of these materials. The dynamic material properties of interest are the complex Young's modulus, shear modulus, bulk modulus, and Poisson's ratio. The area that EB has had the most success in has been determining the complex Young's modulus and the complex shear modulus.

An experimental testing procedure for the determination of the real and imaginary parts of the shear modulus as a function of frequency was developed by EB[6]. Using the procedure, the shear modulus and loss factor as a function of frequency were obtained for the ten rubber compounds formulated under the MART Program, a BQS-6C head mount sample, and a TR 208X boot sample. This testing procedure yielded satisfactory results for the real part of the shear modulus up to frequencies of approximately 5000 cps, but the procedure was found to be unsatisfactory for an accurate prediction of the shear modulus loss factor. This procedure was inadequate for loss factor prediction because the loss factor was sensitive to errors in phase angle measurements.

Under the IDNA program, the quality factor method[7] was used to obtain the loss factor for BQS-6C rubber samples. One problem with this method is that the loss factor is determined at the resonance, therefore the configuration must be changed in order to obtain the loss factor over a range of frequencies. In addition, there is usually a practical upper frequency limit which can be achieved by this technique which is below the maximum frequency of interest for sonar applications.

Testing of rubber compression type mounts was performed by means of transmissibility tests using TR 208A and X transducers[8]. These tests were used to determine mount dynamic stiffness as opposed to basic material parameters. The rubber compounds (EPDM, neoprene, neoprene/natural rubber) were molded into the shape of TR 208X isolation rings and bonded to a transducer test fixture. Using the equations for a simple one degree of freedom system, the mount stiffness and loss factor were determined from the experimental data. This dynamic test procedure gave adequate results up to approximately 1500-2000 cps.

Since all of the above methods, which will be called direct methods, were unsatisfactory for obtaining dynamic properties at sonar frequencies, an alternate approach based on time-temperature superposition was investigated. The time-temperature superposition principle relates measurements made at low temperatures and frequencies to the corresponding values at normal operating temperatures and sonar frequencies. The frequency-temperature conversions are possible because the molecular parameters that control frequency response are affected by temperature reductions [9,10].

A forced vibration instrument, the Rheovibron, is used to measure the Young's modulus and the phase angle of long thin specimens. The Rheovibron measures the temperature dependence of the complex modulus of viscoelastic material at specific selected frequencies of strain input. The frequencies used for this work are 3.5, 11, 35, and 110 Hz. The American Cyanamid Company has done the Rheovibron testing under the supervision of EB.

In a typical test, measurements are made at the four frequencies at temperatures down to -80°C. This data is then reduced [5] to a series of modulus versus frequency curves at various temperatures. By using the time-temperature superposition principle, these curves are shifted in order to obtain a "master" curve which extends over many decades of frequency.

The main limitations of the time-temperature superposition principle are:

(1) The method cannot be used in or near the glassy region of the modulus versus temperature (or frequency) curve.

(2) The method assumes that stress is directly proportional to strain so it is restricted to small deformations.

(3) At temperatures which are more than 120°C above the glass transition temperature, deviations should be expected.

(4) The method as outlined above is applicable only to non-crystalline materials.

EB feels that the time-temperature superposition principle can be used on virtually all the mount materials presently in use, so the superposition principle provides a feasible method of obtaining dynamic properties of mount materials at sonar frequencies. The Rheovibron also has the advantage of measuring basic material parameters rather than stiffness on a complex mount. This allows the data to be applied to mounts of many different designs.

The Rheovibron testing method was used to obtain the dynamic parameters of rubber materials during most of 1971. Prior to this the other testing methods that have been discussed in this section were used to obtain the dynamic parameters.

No satisfactory method has been developed to measure the complex bulk modulus of rubber materials as a function of frequency under the MART Program. This seems to be a state of the art limitation. Dynamic bulk modulus data seems to be very scarce in the literature.

Although they were not applied under the MART Program, two more experimental methods for obtaining dynamic properties of rubber materials should be mentioned. Gottenberg and Christensen [11] have developed an experimental method of determining complex shear modulus of a viscoelastic solid. This experiment involves forced torsional oscillations of a right circular cylinder which is constructed of viscoelastic material. The Rubber Lab at Mare Island Naval Shipyard has an experimental facility for measuring the dynamic elastic and viscous Young's moduli of rubber-like materials [12]. The method used by the Rubber Lab for determining the extensional moduli and mechanical loss factors of viscoelastic materials is the longitudinal-wave transmission method.

Mathematical Models

If an accurate prediction of sonar array performance is desired, the effects of non-rigid interstices must be included. The interstitial area is traditionally composed of water, can structure, rubber and/or structural baffle. Under the MART Program EB has developed math models of various degrees of sophistication for the rubber head and tail mounts in sonar systems. The math models that have been developed by EB are simple spring models, a continuum shear model, and finite element models.

Simple spring models have been used to represent the mounts in the composite math models of the SQS-23 [7] and 3C5 [13] transducers. This method involves calculating the dynamic stiffness (or impedance) of the mount by direct methods similar to those discussed in the previous section. Since these direct methods cannot be used for sonar frequencies, the low frequency results of these direct methods were extrapolated to higher frequencies using the modulus data obtained from time-temperature superposition of the Rheovibron data. One limitation of this model is that the mass of the mount should be small compared to the mass of the components to which it is connected. This type of model will not be valid at frequencies at which a standing wave is established in the mount. Also, for this type of model the actual mount must be fabricated and tested in order to establish the low frequency dynamic stiffness.

A shear continuum model was used as the head mount model in the composite math model of the BQS-6 transducer [14,15] The 3x3 impedance matrix which is the end result of this model requires a knowledge of the shear modulus as a function of frequency so that the impedance matrix can be obtained as a function of frequency. In this model EB assumes that Poisson's ratio is equal to one-half. Since the characteristic dimensions (width and height) of the head mount are small in comparison to the applicable wavelengths, and since the height is much greater than the width, it was assumed that the one dimensional shear equation would adequately describe the response of the rubber. This was later verified using finite element techniques. A derivation of this model is given in Appendix A of Reference 16.

In the free field single element in can analysis of the BQS-6C [17] , EB used the continuum shear model for the head mount and introduced a compressional component through the thickness. They assumed that all dimensions of each rubber math model element are such that the element will satisfy the one dimensional wave equation using some equivalent modulus and thus act as a pure complex spring whose stiffness is that which would be obtained for a short extensional rod ($\frac{A\tilde{E}}{\ell}$) where A = area, ℓ = length, and $\tilde{E}$ = effective Young's modulus. It was assumed that the compressional and shear motion of the rubber head mount are decoupled. Using this "hybrid" model, the mount is represented by a 4x4 impedance matrix.

Finite elements for analysis of incompressible and nearly incompressible materials have been developed at Electric Boat Division [18]. Usual formulations of three dimensional finite elements and two dimensional element stiffness matrices for the case of plane strain are not valid for an incompressible material ($\sigma = 1/2$) due to the quantity ($1-2\sigma$) that appears in the denominator of every term. In addition, for a nearly incompressible material, the solution deteriorates as σ approaches one half. EB feels that the incompressible finite elements must be used when modeling rubber. These two and three dimensional elements contained in the MARTSAM II computer program [19] were used to mathematically model rubber mounts and intersticies in the DC/PA [20], SQS-23 [7], and BQS-6 [14] transducers. The finite element models were used to obtain multi-frequency mobility matrices for input into a composite model for acoustic analysis. By using this method, it is possible to handle complex geometries for which closed form solutions do not exist. The input for an isotropic material requires any two of the following frequency dependent complex material parameters: Young's modulus, shear modulus, bulk modulus and Poisson's ratio.

In the BQS-6 analysis a plane strain finite element of the interstice was generated. The TIM2 triangular incompressible element was used in this analysis. A mobility analysis was performed using the normal mode method and matrix reduction techniques [21]. In addition, a direct solution mobility analysis[21] was performed.

The damping matrix must assume certain forms to be compatible with the normal mode method [21]. For this reason damping of a restrictive nature is considered in the normal mode analysis. In the BQS-6 analysis, the damping matrix [C] was chosen linearly proportional to the stiffness matrix [K] such that:

$$[C] = \alpha/\omega\,[K]$$

where ω is the frequency and α is the damping factor. Assuming this form of damping is equivalent to assuming a complex Young's modulus of the form E (1 + iα) and a shear modulus of the form G(1 + iα). This assumption of equal loss factors for Young's modulus and shear modulus implies that Poisson's ratio is purely real.

The primary purpose of performing a direct solution mobility analysis was to estimate variations in the mobility matrix computed by the normal mode method resulting from possible errors in the damping assumption which is implicit in the normal mode method of solution. A direct solution mobility analysis was done using the same assumptions and material parameters that were used in the normal mode analysis. The elements of the direct solution mobility matrix were in agreement to four decimal places with those of the same matrix computed by the normal mode method. The next step was to solve for the direct solution mobility matrix when the loss factor of Young's modulus was increassed by 10% and the other parameters were unchanged. The resulting mobility matrix was then reduced successively to a 5x5, 3x3 and 2x2 by the same reduction procedures used in the normal mode analysis. A comparison of corresponding terms of all matrices except the 2x2's showed significant differences. These results indicate that the assumption of equal loss factors for E and G is valid if the only significant forces applied to the rubber model are the vertical shearing forces on the two sides where the mount attaches to the head and can.

By assuming the mount is primarily acting in shear,the 3x3 mobility matrices obtained from the finite element approach can be reduced to 2x2's. Inverting these matrices yields the 2x2 impedance matrices. These matrices were then compared with the reduced 2x2 impedance matrix obtained from the continuum shear model. The agreement between these matrices was good [14] , therefore, EB felt that the continuum shear model could be used to adequately model the BQS-6 head mount. They used the continuum shear model in their composite math models.

In order to determine the mobility of the rubber head isolation mount of the SQS-23 transducer EB used a three dimensional finite element [7] . The basic element used in this analysis was a tetrahedral finite element. They combined tetrahedral elements to form an eight-noded solid element (dodecahedron) which they used in the analysis. The normal mode method was used to obtain the mobility matrix in this analysis.

An assumption that has been made in all the rubber math models discussed in this section is that the material behaves linearly for small displacements about some mean displacement at a given temperature and frequency. But, the material parameters of the rubber can be varied enabling an accurate representation of the rubber for small strains over a range of frequency and temperature.

It seems that the importance of the bulk modulus in math models for rubber has not been investigated. In the BQS-6 finite element EB used a measured shear modulus along with an approximate bulk modulus. To accurately calculate Poisson's ratio values of Young's modulus and loss factor or shear modulus and loss factor and the bulk modulus and loss factor are needed. The value of Poisson's ratio is important because for some of these rubber materials it might be possible to use the ordinary finite elements.

Baffle Considerations

In addition to the work on rubber materials EB conducted a study on selection of plastic materials and characteristics for interstices and baffles [22]. The intent of this study was to examine materials for applications where isolation between adjacent units was not a factor.

They attempted to develop a material which would function as a baffle for a top and bottom special cap as in an array configuration like that of MCR47. It is desirable that the baffle material be lightweight, have low damping, and have an impedance which is equal to that of the terminated element. It is considered advantageous to use plastic materials in an intersticial structure configuration for producing the desired impedances without a prohibitive weight penalty. Since it was doubtful that the desired impedance match could be obtained with virgin plastics, the investigation was concentrated on composites made by embedding dense materials in a plastic matrix.

Selected baffle materials of different compositions were fabricated into the form of 12" x 12" x 3" panels. EB fabricated nine different panels and performed baffle reflectivity tests on these panels. A discussion of the test procedure used and the results of the tests can be found in Reference 22.

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FIGURE 1.

EFFECT OF TEMPERATURE ON YOUNG'S MODULUS

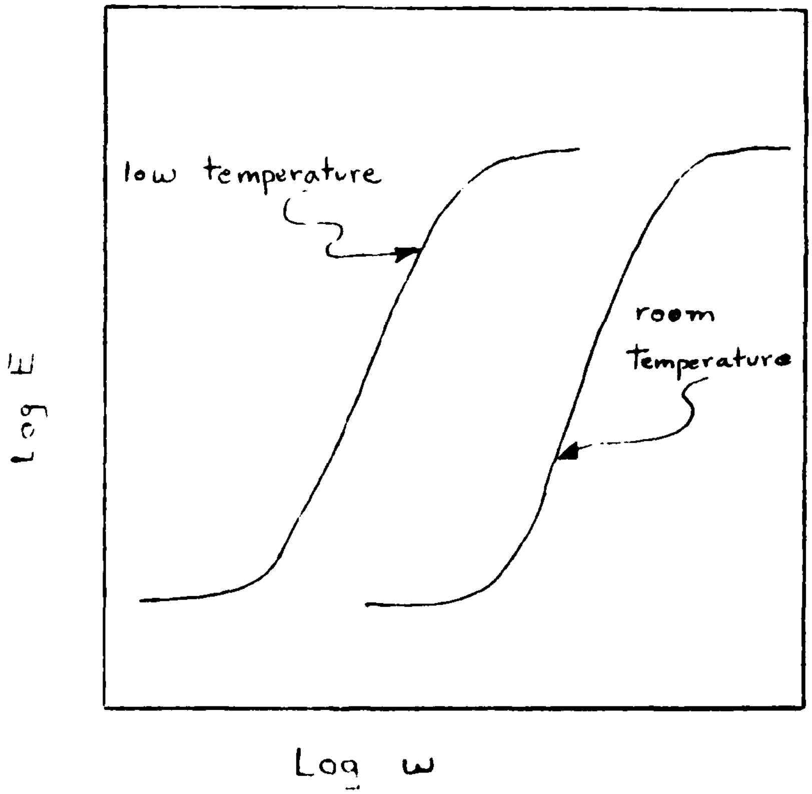


FIGURE 2.

EFFECT OF TEMPERATURE ON LOSS FACTOR OF YOUNG'S MODULUS

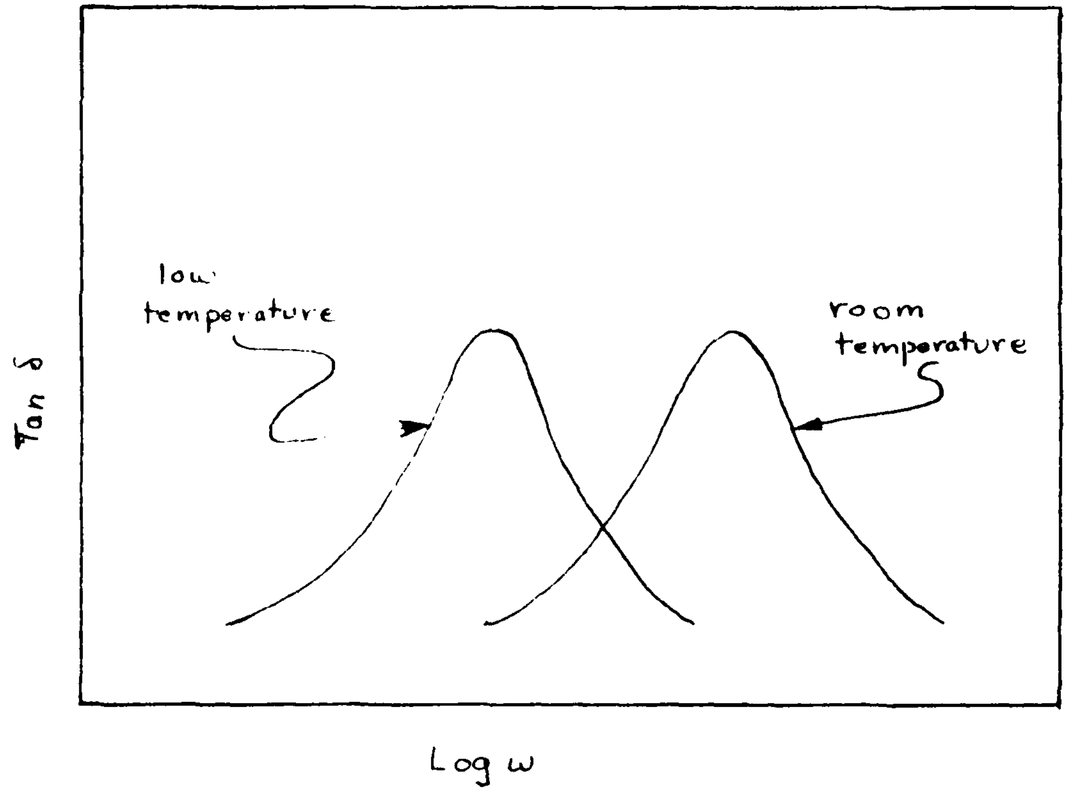
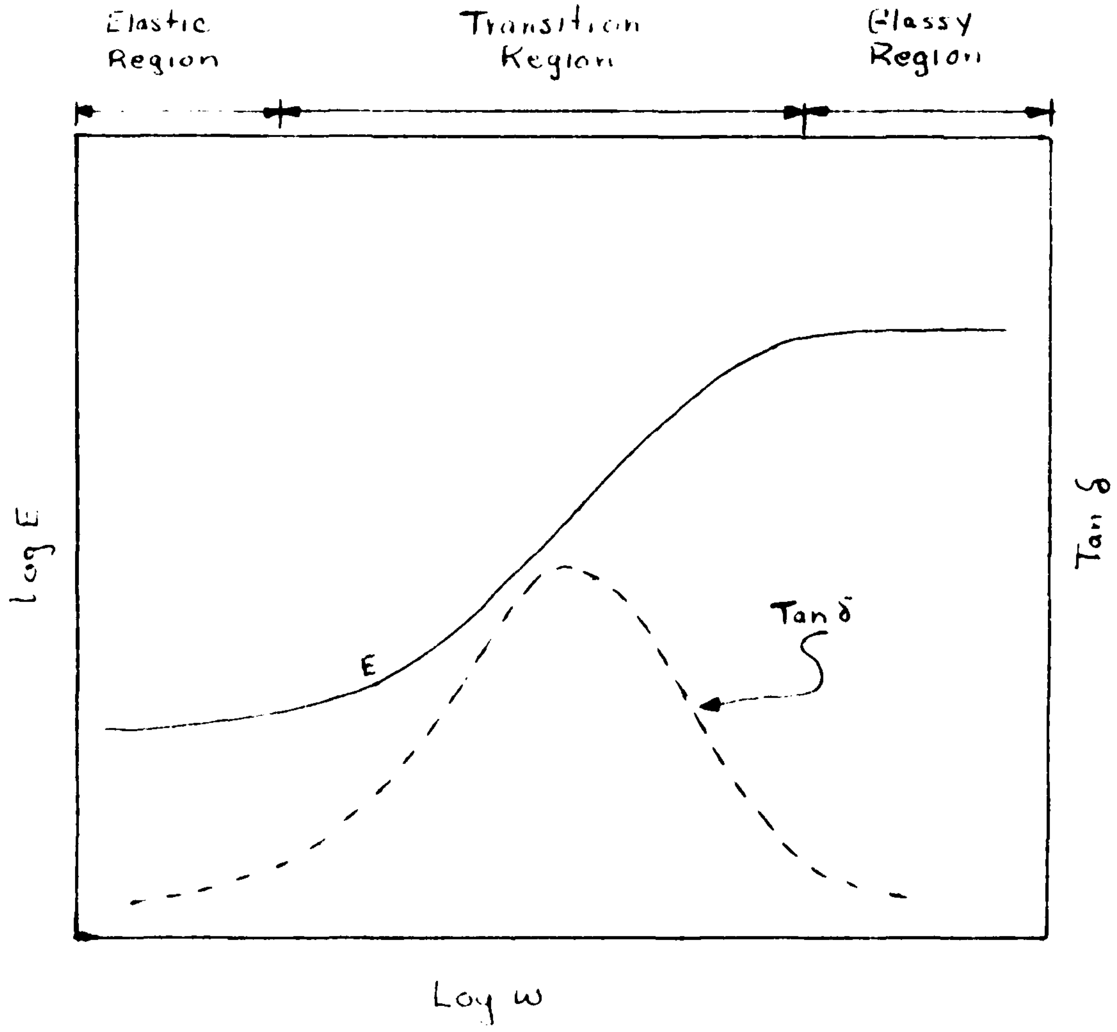


FIGURE 3.

FREQUENCY BEHAVIOR OF RUBBER MATERIALS



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