In three seconds, predict the dynamic performance of rubber

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Compounded rubber is the primary component in timing belts, vehicle tires, vibration isolators and other rubber products, and has to be characterized for different functions depending on these end-use applications. The performance of rubber for these functions can be predicted by investigating various dynamic properties, such as dynamic modulus, static modulus, the ratio (tan delta), phase angle, Yerzley resilience, hysteresis, etc., as per the ASTM D945-16 test method (refs. 1 and 2).

This article will summarize new developments in two different applications of rubber, namely the rolling resistance of vehicle tires and the vibration isolation components. The purpose of testing rubber under simple harmonic oscillation (free oscillation) is to obtain the natural frequency of that sample within 3 seconds (ref. 3 and 4), which is possible by using the AYO-IV Yerzley mechanical oscillograph, manufactured by Tavdi Company, Inc. of Rhode Island (www.tavdico.com).

Tavdi's original interest in the Yerzley technology was with static o-ring seals. These are compressed within a groove and left to prevent fluid movement. The seal is required to maintain an internal stress field to push against the contacting surfaces. In some industries, there are scenarios where a mechanical impact can occur. In this instance, the restraining bolts can be stretched subject to both elastic (recoverable) and plastic (permanent) extension. If the bolts stretch the seal plate and the groove moves apart, the rubber seal is required to move from its compressed geometry to a less compressed geometry, and with lower force will make a new seal by pushing against the remote seal plate. The seal will move at the natural frequency of the compressed rubber. The time that the seal will be open will be within one quarter of the frequency of the natural frequency. The AYO-IV is said to be one of the only machines that will measure this. So, the time for the seal to leak and then reseal following the gap expansion can be calculated. The leakage can be calculated as a volume flow rate for a certain time. This can then be used to ensure that the system can cope with such a leakage, or that contamination is kept to acceptable minimum levels.

Engineers who are designing rubber goods and making products right for their customers now have a tool that compounders can use. Many experimental compounds can be made, and each one evaluated within a few minutes (including setup, triplicate measurement and demounting). The AYO-IV will be particularly helpful for companies that need dynamic property evaluation. The two benefits are the speed of measurement in providing conventional stiffness and tan delta information, and the uniqueness of measuring the natural frequency of the rubber.

By definition, natural frequency is observed in a spring-mass system. In this case, rubber is the spring and the Yerzley oscillograph provides the mass. As long as the loading regime is similar to the actual application, this device indeed measures the natural frequency to be expected in the actual application.

Yerzley predicts the rolling resistance of vehicle tires

A General Tire patent was issued (ref. 5) showing that Yerzley dynamic testing results can be used to predict the rolling resistance of various compounds of rubber for tread applications in tires. There are many different properties that are desirable in automotive tires, and the designers and builders of tires utilize many different rubber blends for different tire components, such as treads, sidewalls, etc., in an attempt to optimize the various properties of the tire. One of the components of a tire is the tire tread component, and this component itself requires many different properties which designers attempt to optimize. For example, lower energy consumption of vehicles is a continuing goal, and one factor in the energy consumption of vehicles is the rolling resistance of the tire, which is a function primarily of the tire tread composition. Additionally, it is desirable to have high wear resistance of the tread to avoid early or premature wear of the tire, which takes place due to normal operation and certain abnormal conditions. Additionally, it is not only desirable, but essential, to have a reasonably good traction of the tire so that it provides the necessary skid resistance to the vehicle. Moreover, it is also desirable to have a relatively low Tg (i.e., glass transition temperature) of the tire in order that the tires will not fail in extremely cold weather. Various ingredients of the rubber compositions, while

Table 1 - Yerzley mechanical oscillograph tan delta (rolling resistance) and Pico abrasion index values of various compounds

Tread vulcanizate properties using emulsion polymers containing isoprene

Polymer Example		*Yerzley tan delta*	*Pico abrasion index*	*IPST, μ-wet*
Compound number	*Bd/I/St**	*Rolling resistance*	*Wear resistance*	*Traction*
1	0/91/9	0.188	80	0.628
2	18/78/4	0.180	86	0.619
3	8/80/12	0.179	80	0.619
4	30/53/17	0.208	83	0.622
5	43/57/0	0.183	92	0.590
6	36/55/9	0.194	85	0.607
7	36/55/9	0.192	88	0.599
8	62/31/7	0.203	91	0.572
9	59/27/14	0.199	88	0.596
10	85/8/7	0.197	91	0.569

*Composition determined 13_C NMR.

improving one property, may adversely affect one or more of the other properties.

Various polymers were blended at a ratio of 50:50 with natural rubber, as shown in table 1, to formulate tire tread compositions. The results of various tests to determine tread vulcanizate properties of these formulations are shown in table 1, specifically the Yerzley tan δ (this parameter is not specified in the standard; it is a measure of energy dissipated by the rubber as it is subjected to vibration) (ref. 4), Pico abrasion index and IPST μ-wet, which are shown for various blends of these rubbers.

The lower the value of Yerzley tan δ, the lower the rolling resistance of the tire; the higher the Pico abrasion index, the better the abrasion resistance of the tire; and the greater the value of the IPST μ-wet, the better traction properties of the tire, as can be seen from table 1. Examples 2, 3 and 5 have the best values for the Yerzley tan δ value, and therefore the best performance with respect to rolling resistance. Examples 1, 2, 3 and 4 have the best μ-wet, thus the best traction. Therefore, compositions 2 and 3 have the best combination of these two values, with example 1 also having a good combination of these values, although all of the examples given are acceptable.

Last but not least, an investigation into the performance of vibration isolation components made of rubber with the aging factor is studied.

Prediction of dynamic characteristics of damping rubbers based on natural and synthetic rubbers

The principal vibration isolating characteristics of rubbers based on natural rubber and a combination of synthetic isoprene and butadiene rubbers were determined. The static and dynamic moduli, the hysteresis losses and the logarithmic decrement were measured on a Yerzley mechanical oscillograph AYO-IV in accordance with ASTM D-945. The changes in these characteristics were measured in the process of heat aging (ref. 6). To convert the data to room temperature, the Arrhenius equation was used. The main changes in the static modulus occur in the first three years, and the main changes in the dynamic modulus in the first five years. Their ratio and the natural frequencies are different for various rubbers and for different storage and service times. The resonance zones are also different. It is concluded that, when predicting the useful life of the vibration isolator, it is necessary to assess all the dynamic and static parameters for each individual case.

There are many scientific studies and standards aimed at determining the service lives of mechanical rubber goods. Most of these are based on the assumption that the rate of the chemical reaction increases with increasing temperature, and for calculations of the change in the physicomechanical properties, different variants of the Arrhenius equation are used. In ISO 11346, an alternative method is proposed for calculating the change in these properties with time using the Williams-Landell-Ferry equation. This equation describes the dependence of time on temperature and makes no assumptions concerning the form of the time dependence of the given property at any temperature. Consequently, it can be applied to any physical property, including the residual deformation and relaxation, or in the case of a complex time dependence of the property. The methods given take no account of the effect of different aggressive media.

While conducting investigations of the durability of mechanical rubber goods by the method of accelerated heat aging, today's scientists rely on their studies of physicomechanical characteristics, such as the strength of the elastomeric material, the elongation at break, the tensile stress, the development of residual compressive deformation and the tangent of the shear angle of phases. These properties cannot fully characterize the useful life of an article operating either under static or under dynamic loading. In this work, the Arrhenius equation was used to determine the change in the properties of rubbers, and the following properties were adopted as the main physicomechanical properties characterizing the life of the vibration isolator: the static modulus, the dynamic modulus, the logarithmic decrement, the development of residual compressive deformation and the hysteresis losses.

In order to calculate the deformation of rubber articles under different loads, values of the static modulus are used, while to calculate their deformation under conditions of dynamic loading, the dynamic modulus is used. These moduli were determined in accordance with ASTM D-945. In spite of the fact that they are calculated in different ways, the dynamic and static moduli are related by the dynamic factor, which is determined experimentally. From the results of the investigations conducted in this work, it was established that not only for each rubber, but also for each formulation, the dynamic factor should be determined individually. These properties, determined on specimens of the material, characterize the rigidity of the end product and, consequently, its natural frequency. The change in these parameters in the process of storage and service leads to displacement in one direction or other of the resonance zone, which occasionally is critical for different navigational and other sensitive systems.

As all rubber and rubber-metal vibration isolators operate under a constant load, it is necessary to take into account the relaxation processes occurring in the material, and also processes of fatigue, which with time lead to an increase in set and to a change in the resonance of the system. For a quantitative assessment of these processes, the development of residual deformation was measured in accordance with GOST 9.029. The development of residual compressive deformation and the values of the moduli do not reflect the ability of a material to

Figure 1 - modification of the static modulus of rubbers based on natural rubber (NR-K) and the combination of synthetic isoprene and synthetic cis-butadiene rubber (IR-K) over time

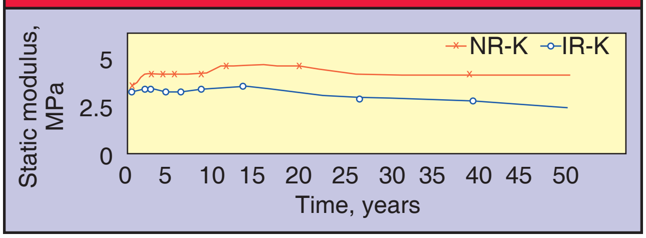


Figure 2 - modification of the dynamic modulus of rubbers based on natural rubber (NR-K) and the combination of synthetic isoprene and synthetic cis-butadiene rubber (IR-K) over time

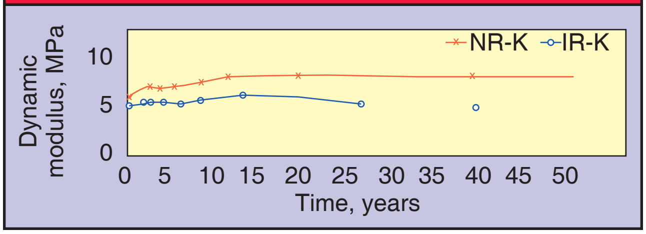


Figure 3 - modification of the dynamic factor of rubbers based on natural rubber (NR-K) and the combination of synthetic isoprene and synthetic cis-butadiene rubber (IR-K) over time

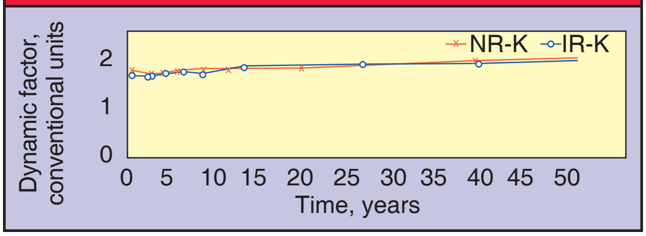


Figure 4 - modification of the logarithmic decrement of rubbers based on natural rubber (NR-K) and the combination of synthetic cis-butadiene rubber (IR-K) over time

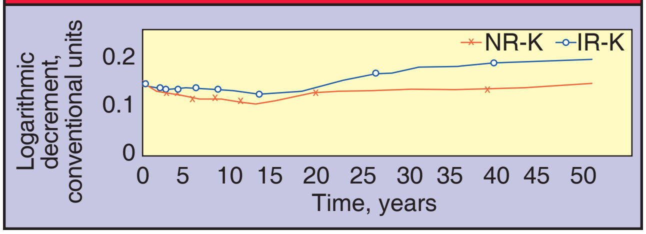
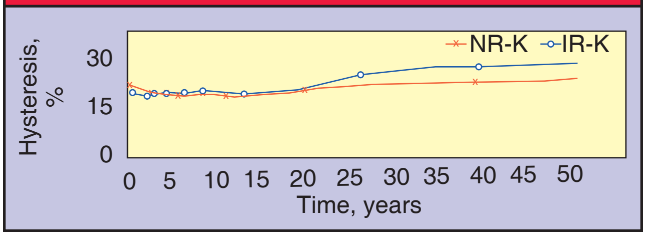


Figure 5 - modification of the hysteresis of rubbers based on natural rubber (NR-K) and the combination of synthetic isoprene and synthetic cis-butadiene rubber (IR-K) over time



dissipate mechanical energy, i.e., do not reflect the degree to which vibration is damped. For a quantitative assessment of the vibration damping ability of the material, the logarithmic decrement was measured. This is calculated as the natural logarithm of the ratio of two successive amplitudes under free damped vibrations. As vibration isolation occurs by the conversion of mechanical energy to thermal energy, it is necessary to assess quantitatively the generated heat to avoid overheating of the vibration isolator. Many different approaches are known for assessing the heat build-up within elastomeric materials under dynamic loads, but they are all based on direct proportionality between the amount of heat generated in unit time and the coefficient of internal resistances, in the calculation of which hysteresis losses are involved. These properties were determined on a Yerzley mechanical oscillograph AYO-IV (ASTM D-945). Tests carried out on the named instrument were conducted in the following way: The specimen (a cylinder of diameter d = 10 mm and height h = 10 mm) is placed between two plates, and displacement in the free state is nullified. Selecting the necessary number of calibrated weights to ensure 20% compressive deformation of the specimen, the weight is dropped from a prescribed height, which ensures free damped vibration. The software of the instrument conducts estimates in accordance with the ASTM and gives the results of tests in the form of a graph of free damped vibrations and a data table. Specimens of a rubber compound based on natural rubber and a combination of SKI-3 polyisoprene rubber and SKD polybutadiene rubber were tested before and after accelerated aging. According to the results of tests and the mathematical processing of data, graphs of combined curves of change in the static (figure 1) and dynamic modulus of rubber compounds based on natural rubber and a combination of SKI-3 and SKD (figure 2) with time were plotted. The results of investigations showed that the static modulus of the rubbers investigated changes significantly only in the first three years (figure 2). It is likely that, in this time, processes (crosslinking, degradation, ring formation, isomerization, the formation of oxygen-containing groups, and so on) are capable of affecting the physicomechanical characteristics of the rubber. The change in the dynamic modulus readings stabilizes five years after the manufacture of the rubber specimen, and they change far less than the static modulus readings (figure 1).

It was established that, with time, there is a change not only in the values of the moduli (figure 2), but also in their ratio (figure 3), which significantly complicates the design of the vibration isolator. Reduction in the amplitude of vibrations on the emergence of resonance is one of the main problems in the design of a vibration isolation system. To determine the coefficient of vibration isolation (η), which characterizes the degree to which the amplitude of vibration effects are reduced, the following equation is used:

$$\eta = \frac{\sqrt{1 + \left(\frac{f_f}{f_n}\right)^2 \frac{4\nu^2}{4\pi^2 + \nu^2}}}{\sqrt{\left[1 - \left(\frac{f_f}{f_n}\right)^2\right]^2 + \left(\frac{f_f}{f_n}\right)^2 \frac{4\nu^2}{4\pi^2 + \nu^2}}}$$

where f_f is the forced frequency of vibrations, Hz; f_n is the natural frequency of vibrations of the vibration-isolating system, Hz; and ν is the logarithmic decrement of the elastomeric material used for the manufacture of the vibration isolator. On the emergence of resonance, the given equation will take the following form:

$$\eta = \sqrt{1.25 + \frac{9.86}{\nu}}$$

From this, it can be seen that reduction in the logarithmic decrement leads to an increase in the amplitude of vibrations, which often can be critical for the protected element. The results of the investigations showed that the trend of change in the logarithmic decrement is identical for a rubber compound based on natural rubber, and for a rubber compound based on synthetic rubber (figure 4). However, there is a correlation between the logarithmic decrement and the hysteresis losses. The increase in hysteresis losses leads to an increase in the heat build-up within the vibration isolating material, which often has a negative effect on the life of the vibration isolator.

Consequently, during the operation of vibration isolators manufactured from the investigated materials, the maximum amplitude at resonance will be achieved in a period from 10 to 15 years, but here the heat build-up will be minimal. From the results of investigations of the development of residual compressive deformation, it can be seen that, during the operation of the vibration isolator, constant displacement of the resonance zone will occur with time, and here the direction of this displacement will depend not only on the shape of the working element of the rubber mass, but also on the type of deformation. Thus, before carrying out studies to determine the service lives of vibration isolators, it is necessary to rank their main characteristics on the basis of their service conditions.

In the design of vibration isolators, account must be taken of the fact that, with time, the corollary relationship between the characteristics (for example, between the dynamic and static moduli) can change in one or other direction.

Conclusion

As the data show, this machine can produce results that can be used to predict how rubber components will behave during their useful life cycles. It is also economically a very feasible testing machine. Therefore, the AYO-IV is predicted to serve the rubber industry for many more decades to come.

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