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CHARACTERISATION OF VIBRATION ISOLATORS USING VIBRATION TEST DATA

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Abstract

Vibration isolators, usually made from viscoelastic materials, are used to suppress excessive vibrations in many applications. However, the optimisation of vibration isolators is a difficult process mainly due to inherent dependency of the properties of viscoelastic materials to many factors, including temperature, frequency and strain. It is therefore necessary in many cases to identify the characteristics of vibration isolators using experimental techniques.

There are well-established experimental procedures for the determination of the dynamic properties of vibration isolators or viscoelastic components in general. However, these procedures mostly requires expensive testing equipments including hydraulic testing machines equipped with various controllers and sensors. This paper presents two approximate methods for the determination of dynamic properties of vibration isolators or similar components exhibiting elastic and damping nonlinearities without the need for dedicated hardware.

INTRODUCTION

Vibration isolators are used in many applications to minimize the transfer of vibrations from machines to foundations. This is almost always the case in domestic appliances, a typical example being refrigerators where vibration isolators are used to minimize the structural borne noise due to the vibrations of compressor. For this particular case compressor grommets are the vibration isolators which are used to minimize the transfer of vibrations from compressor to refrigerator body. However, the optimisation of such isolators is a difficult process, one aspects of the difficulty being the dependency of viscoelastic materials, from which most isolators are made, to many

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factors including frequency, temperature and strain. Therefore, it is often necessary to determine the dynamic properties of vibration isolators before any optimisation process.

There are well-established experimental procedures for the determination of the dynamic properties of vibration isolators. Direct Method [1, 2] is a well-known traditional method. Other methods for characterizing vibration isolators have also been developed: 'Indirect Method' [1, 3, 4], 'Transfer Function Method' [5] and others [6, 7]. A common feature of these methods is that they all need expensive hardware with sophisticated actuators and control systems. It is desirable to have some alternative means for estimating the dynamic properties of vibration isolators without having to resort to such systems, or when such systems are not available to engineers.

This paper proposes two simple methods that can be used for estimating the dynamic behaviour of vibration isolators using basic vibration testing equipment. It is shown in this paper that linearised properties of vibration isolators can be estimated with acceptable accuracy for various applications by measuring the input and output signals of a system comprising a rigid mass and one or more vibration isolators. The second method aims to estimate non-linear stiffness and damping properties of vibration isolators by measuring the response of the system only.

OVERVIEW OF THE PROPERTIES OF VISCOELASTIC ISOLATORS

Dynamic properties of viscoelastic isolators exhibit temperature, frequency and strain (static and dynamic) dependence [8-9]. It is also known that such isolators show softening behavior, known as creep [10] under static preload and Mullins [11] effect under constant strain cycles. It is obvious that measuring the properties of viscoelastic isolators as a function of all these variables is a complex and expensive task. Therefore, depending on the objectives of the test, some of the variables might be ignored or kept constant during the measurement. In some cases, further steps are taken to eliminate some of the variables. For example, it is suggested in [12] that softening behavior of viscoelastic components can be removed if high strain dynamic loadings are applied to such components before the measurements are made.

All the measurements presented in this paper are performed at room temperature, hence the temperature effect is not investigated. However, it is aimed at investigating the effect of strain and frequency on the dynamic properties of vibration isolators. Furthermore, the measurement techniques presented in this paper are demonstrated using a specific type of compressor grommets as shown in Fig. 1. Also shown in the same figure is the structural model assumed for such isolators.



Fig. 1 Compressor grommet and the structural model

ESTIMATION OF DYNAMIC PROPERTIES OF VISCOELASTIC VIBRATION ISOLATORS

Estimation of Isolator Properties using Frequency Response Function



This approach aims to estimate frequency-dependent (but amplitude-independent) stiffness and damping properties of the isolator by establishing a SDOF system shown in Fig.2, comprising a viscoelastic isolator (k*) loaded by a rigid block with mass M where the isolator mass m is negligible compared to M. The approach here is to measure the Frequency Response Function (FRF) of the system by measuring the response - say acceleration a(t) - and the excitation force without any control, and processing them to obtain the system FRF. The measured FRF can then be processed using modal analysis techniques to obtain the natural frequency and the damping of the system. Finally, the modal parameters are related to the isolator stiffness and damping properties as:

$$k_{real} = M f^2, \qquad k_{im} = k_{real} \eta, \qquad |k^*| = \sqrt{k_{real}^2 + k_{im}^2}$$
(1)

where *f* is the natural frequency, η is the loss factor, k_{real} and k_{im} are the real and imaginary parts of the isolator stiffness respectively.

It is obvious that the amplitude non-linearity cannot be measured using this approach although the procedure is very fast and can provide a quick, yet quite approximate properties of the isolator. It must be noted however that the frequency-dependent properties can be estimated by repeating the measurements using various rigid blocks with different mass properties. It is also worth noting that measurements are made under static strain due to the preloading of block mass M.

Estimation of Isolator Properties Using Log Decrement Method

The method of estimating the dynamic properties of isolators described in this section is based on the same SDOF system shown in Fig.2. However, a distinct feature of the method proposed here is that it does not require the measurement of the force applied to the system. It is therefore only necessary to measure the response signal, e.g., acceleration a(t), hence the measurement process is even simpler than that of the previous section although processing the signal using the Log Decrement Method is somewhat more complicated.



Fig.3 Transient response of a)Linear SDOF system, b)Nonlinear SDOF system

The use of the Log Decrement Method is a well-established technique for the estimation of the modal properties (natural frequency and damping) of a linear SDOF. This is illustrated in Fig.3a in the case of a typical transient signal where the signal amplitude decays exponentially and the period T between the consecutive cycles remains constant. These properties lead to well-known relationships between the log-decrement (δ), structural damping (η) and the natural frequency f of the system:

$$\delta = \frac{1}{n} \ln \frac{A(t_i)}{A(t_i + nT)}, \qquad \eta = \frac{2\delta}{\sqrt{4\pi^2 + \delta^2}}, \qquad f = \frac{1}{T}$$
(2)

where $A(t_i)$ is the modulus of the peak response at time t_i (i.e., $A(t_i) = |A(t_i)|$) and n is number of cycles after t_i . If the system is linear, the same modal properties are obtained irrespective of which cycle or how many cycles are used in the evaluation of the above equations. When the system is nonlinear, however, the arguments stated above are no longer valid; the modal properties estimated using Eq.(2) will vary depending on the amplitude at which these properties are estimated. This is precisely the property that will be utilized to extract as much information as possible from the transient signal about the amplitude- and frequency-dependent properties of viscoelastic isolators although the frequency and the amplitude will be interrelated. The idea behind this approach can be described in connection with a transient signal in Fig.3b for a nonlinear SDOF system. As indicated in Fig.3b, the period T will be different for each cycle as the transient response decays and the peak amplitudes of individual cycles A_i and the corresponding time t_i can be determined using experimental data. This makes it possible to estimate the dynamic properties of viscoelastic isolators as a function of amplitude and frequency by using the logdecrement method in a piece-wise fashion as summarized in Eqs.(3-4). Once the natural frequency and the damping factor are known as a function of displacement amplitude X_i , the real and imaginary parts of the isolator stiffness are calculated according to Eq. (5). It should be noted that the particular implementation adopted in this paper makes use of all the peaks and it is well suited for noisy data as some kind of averaging is involved. It is also worth restating that the measurement procedure summarized here provides stiffness and damping properties of viscoelastic components as a function of amplitude and frequency. However the amplitude and the frequency are not independent from each other.

$$\delta_{i} = \ln \left(\frac{A_{i-2} + A_{i-1}}{A_{i} + A_{i+1}} \right), \qquad \eta_{i} = \frac{2\delta_{i}}{\sqrt{\delta_{i}^{2} + 4\pi^{2}}}$$
(3)

$$f_{i} = \frac{1}{0.5(t_{i+1} + t_{i}) - 0.5(t_{i-1} + t_{i-2})}, \qquad X_{i} = \frac{0.5(A_{i} + A_{i-1})}{(2\pi f_{i})^{2}}$$
(4)

$$k_{real_i} = M f_i^2, \qquad k_{im_i} = k_{real_i} \eta_i$$
(5)

EXPERIMENTAL STUDY

Experimental Setup



Fig.4 a) Setup for 'Estimation of Isolator Properties using Frequency Response Function'. b) Setup for 'Estimation of Isolator Properties Using Log Decrement Method'. c) Mathematical model of the system

The experimental setup used in this study is aimed at obtaining an equivalent SDOF system in Fig.2. As illustrated in Figs. 4a and 4b, the test rig consists of two blocks of mass, one at the base glued to the ground and the other on the top acting as a rigid mass M. In between these two blocks, there are 3 compressor grommets, properties of which are assumed to be identical. The mathematical model of this SDOF system can be represented as in Fig.4c. This system can be excited using an instrumented hammer (Fig.4.a) or using an ordinary hammer (Fig.4b). In both cases, special care was taken in selecting the hammer tips so as to ensure that only the SDOF mode of vibration is excited.

Results

All the results presented here are obtained using a rigid mass of 10 kg, i.e., M=10 kg. As stated before, 'Estimation of Isolator Properties using Frequency Response Function' required measuring both the impact force and the response level using the

setup in Fig.4a. A sample FRF is illustrated here in Fig.5 and the repeatability of the measurement results are tabulated in Table1 for three independent measurements.

A typical acceleration measurement illustrated in Fig.6 demonstrates the application of the so-called 'Estimation of Isolator Properties Using Log Decrement Method'. In Fig.6, only the peaks marked with arrows are used in the calculations since the initial peaks indicated build-up period. Processing the data in Fig.6 yields the dynamic stiffness and loss factor as presented in Figs.7 and 8 respectively. Repeating this process for many measurements can also provide statistical information, as illustrated in Figs.9 and 10 for the case of 50 independent measurements.

The results of the proposed methods are also compared against those obtained via 'Direct Method' measurements according to ISO 1846-2 standard using MTS 831 material testing system at the same preload and preloading time conditions (same static strain). The comparisons are given in Fig.11 at a specific response level (i.e., 0.05 mm). It seems that the approximate methods proposed in this paper slightly overestimate the dynamic properties of the isolators compared to those of the MTS system. However, the results can be quite acceptable for many applications considering the variations of the properties of nominally identical isolators.



Meas. No	Natural Frequency (Hz)	Dynamic Stiffness (N/m)	Loss Factor η
1	24.39	79994	0.226
2	24.42	80217	0.228
3	24.12	78326	0.234

Table 1 Results of repeatability tests

Fig.5 Sample results for 'Estimation of Isolator Properties using FRF'



Fig. 6 The use of the peak amplitudes for the 'Estimation of Isolator Properties Using Log Decrement Method'

CONCLUDING REMARKS

Two approximate methods have been presented in this paper for the measurement of the dynamic properties of viscoelastic components without the need for expensive and dedicated hardware. The first method is, in effect, based on linearising the system, hence provide a quick, yet 'average' values for the component properties. The socalled 'Estimation of Isolator Properties Using Log Decrement Method', on the other hand, aims to provide amplitude-dependent parameters for the component under test. Another advantage of the second approach is that it requires perhaps the simplest test rig since the response of the system only needs to be measured. The test results are verified using a dedicated Material Testing System. It is found that the estimated parameters can be acceptable for many purposes. It is however worth noting that the use of the proposed methods for wider frequency range requires performing repetitive tests, the nominal natural frequency of the SDOF system being adjusted each time.

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Fig.7 a) Modulus of dynamic stiffness against amplitude (single measurement)b) Modulus of dynamic stiffness against frequency (single measurement)



Fig.8 a) Modulus of loss factor against amplitude (single measurement) b) Modulus of loss factor against frequency (single measurement)



Fig.9 a) Modulus of dynamic stiffness against amplitude (50 measurements) b) Modulus of dynamic stiffness against frequency (50 measurements)







Fig.11 Comparison of equivalent results with those obtained using Direct Method. (Amplitude:0.05 mm, MT-1,2,3: Based on FRF, LD: Based on Log-decrement, DM-g1,2,3: Based on Direct method for individual grommets)