An energy dissipation approach on complete loading-unloading and dynamic impact predictions with experimental verification for rubber anti-vibration component

Robert Keqi Luoa, b, *, Weidong Wanga, Qingyuan Xua, Xuebing Lic

a Department of Railway Engineering, School of Civil Engineering, Central South University, Changsha, Hunan, 410075, China
b Department of Engineering and Technology, Trelleborg IAVS, Leicester, LE4 2BN, UK
c Department of Automotive Engineering, Tsinghua University, Beijing, 100084, China

Abstract

Accurate evaluations of a completed loading-unloading cycle and dynamic impact response for rubber anti-vibration components have been very challenging for industry over many years. In this article, we have altered the classic hyperelastic models to predict complete loading-unloading response using an energy dissipation approach. In addition, we proposed NFR (Natural Frequency Region) approach to simulate a dynamic impact event instead of using the usual viscoelastic methodology, as results from different viscoelastic models may vary widely and to avoid complex parameter fitting procedures. The proposed approaches have been validated in laboratory experiments using industrial anti-vibration components. We have also detailed a procedure for engineers to implement this approach in commercial finite element software without writing intricate user subroutines, as simulation based on finite element method has been routinely used in industry to support design of new products. It is suggested that these methodologies could be used for a design stage in engineering applications.

1. Introduction

Rubber anti-vibration systems have been widely used in engineering applications in order to minimize vibration effects generated from a dynamic environment. In the current design of rubber components in industry, one of the most important design parameters, i.e. stiffness (load-deflection curve), is only referenced on a loading portion of a loading-unloading history [1–3]. It is well known that there is substantial difference between the loading path and the unloading path for rubber components. The unloading path is always softer than the loading path. There are notably limited reports in the literature that consider this “stress softening” effect in the design of rubber products used in industry. Many researchers [4–6] have adopted a “damage” approach to simulate this phenomenon. Ogden and Roxburgh [7,8] modelled this loading-unloading situation using a single (softening) variable. Gornet et al. [9] used a constitutive damage model and integrated with Abaqus software. Praffcke and Abraham [10] tried manually correcting the relevant parameters with commercial software Abaqus, and concluded that progressive stress-softening damage was not effectively supported by the software. It would be more practical to adopt more simplified approaches. Luo et al. [11–13] proposed an engineering approach for several rubber anti-vibration products. Up to now, the stress softening behaviour is still recognised as a major obstacle in industry to correctly predict the response under external loading conditions.

In dynamic environments, accurate evaluations of dynamic impact responses for rubber anti-vibration components have been very challenging for industry over many years, especially for solid rubber components. A solid rubber component can be simplified into an element with stiffness and damping if the stress and the strain of the component itself is not the main concern [14–18]. This simplification for rubber anti-vibration components is essential for engineering structures. Luo et al. [19,20] used spring and damping elements to replace rubber suspension systems for dynamic analysis of a rail vehicle which has led a successful fatigue assessment on a bogie structure. Grassie [21] utilized a lumped spring-damping system to calculate the dynamic stiffness of a rubber pad and made a good comparison between a laboratory test and a section of real

* Corresponding author. Department of Engineering and Technology, Trelleborg IAVS, Leicester, LE4 2BN, UK.
E-mail addresses: Luo0801@gmail.com, Robert.luo@trelleborg.com (R.K. Luo).
A viscoelastic approach has usually been utilized if the dynamic characteristic of a solid rubber component is a main concern. Kelvin-Voigt, Maxwell and fractional Kelvin-Voigt models have been employed for evaluation [23–29]. A free oscillation technique to measure the dynamic storage and the loss moduli of rubber samples was investigated in Ref. [30]. It was observed that pre-strain did not have a strong influence on the dynamic storage and loss moduli. A one-dimensional model with three-layers was used by Austrell et al. [31] to simulate a rubber bush response under a stationary cyclic load. Shi et al. [32] developed a one-dimensional spring model with five parameters for a rubber component calculation. However, there are major issues either in accuracy or in complexity with viscoelastic models [33].

Another approach to include rubber hysteresis is to consider the Rayleigh damping, which has been widely used in structure dynamics involving linear and non-linear materials as well as composite materials [34–38]. Luo et al. [39,40] found that loading frequency change had notable influence on dynamic response and tried to incorporate the Rayleigh damping into rubber simulations using one-dimensional solid elements. Their work achieved partial success. Suarez et al. [41] performed a PSD analysis on resilient wheels and compared those with traditional ones. Wei et al. [42] observed the stiffness change with frequency of a rubber pad in addition to temperature effect and noticed significant effect of a higher frequency range.

For engineering applications, there are very limited literature on complete loading-unloading and dynamic impact evaluations for solid rubber anti-vibration components. In this article, we first describe experiments on an industrial product under a quasi-static event and a dynamic impact condition. Then, an energy dissipation approach for complete quasi-static loading and a natural frequency region method, developed from Rayleigh damping, are presented, concluding with experimental validation following simulation of the component.

2. Static and dynamic impact experiment

An industrial anti-vibration product, so called CH (circular hydro) mount, has been used for this integrated simulation-experimental procedure. This component is shown in Fig. 1. The rubber part was based on natural rubber with shear modulus of 1.4 MPa. The diameter of the product is 105 mm and the height is 65 mm with three interleaves. This type of product is intended for a higher end use to reduce the vibration effect from a dynamic environment. This type of mount is usually installed in a pair with a centre plate in the middle section. There is a 2 mm diameter hole in allow fluid to move between the upper and the lower chambers. The object of this design is to obtain extra damping for noise attenuation and motion control.

Load-deflection responses are usually needed in anti-vibration applications under a quasi-static condition. Therefore, we first performed a quasi-static experiment to obtain a load-deflection curve. The CH components were mounted in a pair similar to a real installation with 5 mm preload at both ends in the vertical direction. A load-deflection curve up to approximately 15 mm, that is at least 50% over the required loading, in both positive and negative vertical directions, was recorded. A part of the curve in a positive vertical direction is plotted in Fig. 2. In many engineering applications, only an unloading portion of the response is needed and forms a base for stiffness calculation. In recent developments, an unloading portion of loading-deflection procedure is also required to assess hysteresis of an anti-vibration system. This quasi-static experiment was also necessary to verify the material properties for further dynamic and impact evaluations as the spring stiffness is directly linked to the elastic property of the rubber material.

In a dynamic situation, the behaviour of the rubber anti-vibration components are substantially different from the quasi-static condition due to damping and mass effect. In a real service environment of rail vehicles, for example, rail track irregularities generate various dynamic events on suspensions and engine installations. The system components most affected by the dynamic loads are the rubber anti-vibration components. To evaluate the performance of the rubber components, a dynamic impact experiment was carried out on these CH mounts that were fixed in a test rig. A 250 kg mass was dropped on the rubber springs at a velocity of approximately 440 mm/s in a vertical direction. Digital record equipment was used to collect the deflection response from these components. A sample of the deflection history in a range of approximately 0.45 s frame is plotted in Fig. 3. The maximum impact deflection is approximately 8 mm which occurred at the first peak. The main response frequency after the impact peak is approximately 8.5 Hz.

3. Constitutive models and simulations

The general dynamic equations [43] can be written as

\[ M\ddot{\delta} + C\dot{\delta} + K\delta = \{F\} \]  

(1)

where \([M]\) is the system mass, \([C]\) is the system damping, \([K]\) is the system stiffness, \(\dot{\delta}\) is the deflection vector, \(\dot{\delta}\) is the system velocity vector, \(\ddot{\delta}\) is the system acceleration vector, and \(\{F\}\) is the external force vector.

Equation (1) can be used in both linear and non-linear conditions. For quasi-static analysis, the system mass matrix \([M]\) and the system damping matrix \([C]\) can be ignored. The system stiffness matrix \([K]\) is linked with the elastic part of the rubber material. In industrial applications, a hyper-elastic model, based on strain energy density, is usually utilized for rubber materials. For rubber anti-vibration components, equation (1) concerns non-linear dynamics. The Hilber-Hughes-Taylor time integration method was used to solve equation (1). The stiffness matrix \([K]\) was inverted and a set of simultaneous nonlinear dynamic equilibrium equations were solved at each time increment. This solution has been done iteratively using Newton’s method. More details can be seen in Ref. [44]. Our approach was implemented in the finite element software Abaqus using user subroutines and/or user input data.

3.1. Rubber material model and quasi-static simulation for uploading

A quasi-static simulation provides insights into the elastic behaviour of the rubber anti-vibration component. The response of a system subjected to a quasi-static load can be expressed by the following equation

\[ K\{\delta\} = \{F\} \]  

(2)

In order to predict the quasi-static response, an appropriate material model should be used. There are several hyper-elastic models are used to describe rubber material based on the strain energy density [44,45]. These classic hyperelastic models can be expressed in a general form:
دریافت فوری متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات