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ORIGINAL ARTICLE

Modal analysis on tire with respect to different parameters

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Abstract This paper presents experimental modal analysis of non-rotating tires under different boundary conditions. A test rig with four guides in vertical (radial) direction and two guides in axial direction was designed to support the tire-rim assembly with a free support. The setup permits to carry out the experiments on the grounded supported tire-rim assembly while changing the value of the static load acting on the wheel axis. Under static load condition, it is found that, tire deflection depends on the applied static radial force in a hysteresis manner and a third-order polynomial was used to fit the data during loading and unloading conditions. The relationship between static stiffness in radial direction and tire deflection is nonlinear and depends on loading/unloading conditions for different tire pressures. The response of the tire is quite similar to the response of viscously damped mass system for impulse force which is provided by an impact hammer. The results show that the system modal parameters can be obtained respective of loading or unloading conditions with a maximum difference of 1.992% for frequency values and 3.66% for damping values. This study has a practical value for the description of mechanical properties of tires.

1. Introduction

The requirements for automobile dynamic characteristics become higher due to increase of automobile speed. The automobile contacts the road surface through tires, which will affect the behavior of the automobile significantly. The requirements for tire are high abrasion resistance, optimum stiffness characteristics and low rolling resistance [1]. Due to the complex structure of tire, modal analysis is a powerful means for the study of dynamic characteristic of tires. The tires are influenced by the complex structure and the working conditions, and it is difficult to separate their effects. Using modal parameters identified by experimental modal analysis technique to determine the dynamic behavior of a tire reflects its intrinsic characteristics. Such analysis must be independent of the tire working conditions [2], and should be identified via modal test in dependant of the ambient conditions. Thus experimental modal analysis on tires will be more reasonable and can be standardized. In this paper the related issues have been studied and discussed carefully. The following aspects

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must be investigated in the experimental modal analysis of the tires:

1. The type of support of the tire (i.e., fixed support or freely suspended).
2. The means of excitation (i.e., using impact hammer or electric exciter).
3. The selection of the sensors to reduce the additional mass and stiffness of the tested object as much as possible.

In order to obtain reliable test results with sufficient accuracy, it is important to eliminate the error of measurement arising from aliasing and leakage which are inevitable in frequency domain analysis.

Modal analysis of passenger vehicle tires started in 1960s. A major contributor to this study was Pacejka [3] who proposed a semi-empirical tire model known as the magic tire formula. His experiments focused on comparing the behavior of bias play with new radial tires. The experiments were carried out using a fixed axle test setup with radial excitation. Considerable amount of work has been done by Zegelaar [4] and Yam et al. [5] to examine the three dimensional mode shapes of passenger tire. Zegelaar examined the in-plane vibrations of such a tire in free and standing conditions. Experimental modal analysis is performed by placing tri-axial accelerometers around the tire tread and hitting the tire in various places with a modal hammer. The input force from the hammer is recorded along with the outputs of the accelerometers in order to determine the frequency response function between the input and output force. The experimental results were compared with analytical results derived from the flexible ring model proposed by Gong [6]. Yam et al. [5] used a similar test setup and analyzed the full three-dimensional motion of the tire to get its in-plane and out of plane vibrations. Their results showed that the first flexible mode occurs around 120 Hz, which agrees with Zegelaar's results. In the analysis by Yam et al. only the free tire modes were examined. There are number of methods that have been used for examining the presence of nonlinearities in experimental modal testing. Sine sweep and harmonic input tests can be particularly useful for detecting effects such as nonlinear resonances. Exciting the system at one-half, one third, twice, and three times the linear natural frequency can reveal nonlinear resonances that are common nonlinear systems [7]. It is quite common for sinusoidal inputs at one frequency to excite a resonance at a different frequency in a nonlinear system. This does not happen in a linear system, and a slow sine sweep test of a harmonic excitation is useful to detect such an occurrence. Superposition is only strictly valid for linear systems. The superposition principle can be used to detect nonlinearities in a system by observing deviations from linear superposition [8]. Nyquist plots are also on way to detect nonlinearities. For linear system excited close to resonance, the Nyquist plots are circular. For a nonlinear system, the Nyquist plots can become distorted into ellipses or other shapes [7]. Nonlinear resonances may be a problem in experimental modal analysis. The excitation of one mode at a particular frequency can lead to a response at another frequency as well as participation of other modes. Chanpong et al. [9] carried out experiments to measure the frequency response function for four different settings which were aluminum alloy rim assembled with a tire and mounted on a stand, aluminum alloy rim assembled with tire and placed on a soft cushion, a steel rim assembled with the tire and mounted on a stand and finally a steel rim assembled with the tire and placed in a soft cushion. The soft cushion support was equivalent to free support. The roving impact test was applied to the rim in order to identify the natural frequencies of both aluminum alloy and steel rims. The frequency response data of roving impact hammer tests on a wheel tire assembly were processed using MES cope software for identifying its mode shape. Their results have shown that the significant vibration response amplitude peak is between 200 and 250 Hz which is related to the tire cavity resonance noise. A detailed investigation on the available tire models with a description of their capabilities and application areas has been provided by Ammon [10], Lugner and Plöchl [11], and Lugner et al. [12]. Most tire models typically consist of two separate parts. The first part is represented by the structural modal analysis which describes the structural stiffness, damping and inertia properties of the tire. The second one is the tread/road contact model which is able to furnish an estimation of the contact pressure distribution and the distributed friction force. Many authors suggest direct methods for estimating the tire parameters. They are based on embedded sensors, such as strain gauges [13], surface acoustic wave [14] or MEMS sensors [15], which allow direct measurement of the tire deformations or tiring surface vibrations.

The main objective of this study was to determine the natural frequencies and the modal damping ratios of a passenger vehicle tire. The experiments are carried out for both a free tire setup suspended from above and a free tire support using a soft cushion. Then, a new design of a test rig is introduced to support the tire with a free support in both radial and axial directions. Also, the tire can be treated as a fixed support in radial and axial directions. The results of the freely suspended methods and the new experimental test setup are to be compared. The setup permits to carry out the experiments on the freely supported tires while changing the load on the tire.

2. The types of support of the tire-rim assembly

The tire-rim assembly may be tested in a free condition or grounded [16]. Free condition means that the test object is not attached to ground at any of its coordinates and is, in effect, freely suspended in space. In this condition, the structure will exhibit rigid body modes which are determined solely by its mass and inertia properties. In practice, it is not possible to provide a truly free support but it is generally feasible to provide a suspension system which closely approximates this condition. This can be achieved by supporting the structure on very soft springs such as a light elastic band [17]. Also, the steel-rim may be assembled with a tire placed on a soft cushion. The soft cushion support is equivalent to a free support [9]. The type of support is referred to as grounded because it attempts to fix a selected point on the tire to the ground. A new modal analysis test facility is designed and installed. Fig. 1a shows how the tire is suspended by a light elastic band, while Fig. 1b shows the suspension of the tire using very soft springs provided in the test rig. The rig has four vertical guides with linear bearings to provide the movement of the tire assembly in vertical direction while neglecting the friction effect of the guides. This is equivalent to the free support using the elastic band. Fig. 2a illustrates the free support of the tire assembly using a soft cushion, and Fig. 2b shows that the test rig may be

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