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ENGINEERED MODEL FOR THE NUMERICAL INVESTIGATION INTO VIBRATION CHARACTERISTICS OF A NOVEL BRIDGE BEARING UNDER FREE-FREE AND FIXED BOUNDARY CONDITION

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Abstract. *One of the most significantly deteriorated causes of bridge bearing failure is the resonance under various vibration conditions. It is important for bridge engineers to prevent the phenomenon, also called resonance, occurs to provide large amplitude vibrations when the bridge is being forced to vibrate at its natural frequency. This may lead to failure of the bridge structure under resonant vibrations. Common bridge bearings cannot well perform when vibrated large for example elastomeric bearings. This is because they do not have adequate mechanical properties to resist extremely various loads. Therefore, the concept of using metastrcutures to gain superior mechanical properties inspired us to generate a novel bridge bearing model. Because of the nature of dynamic forces on bridge structure, the vibration characteristics of a novel bridge bearing are crucial in analysis and design processes. This paper is the world's first to focus on the comprehension of vibration characteristics of a novel bridge bearing under free vibration. Through finite element method using Fusion 360 software, the numerical investigation of the modal parameters under dynamic condition was carried out for the novel bridge bearing. Also, there is a comparison of the free vibration results between the free-free and fixed boundary condition, in order to observe the influence of various boundary conditions responding to fundamental frequencies and mode shapes of a bridge structure. Additionally, to verify and develop a numerical model of bridge element, the free oscillation characteristics of the novel bridge bearing in different loads and boundary conditions are required. It is confirmed that vibration response measurements and parameters of a novel bridge bearing will be useful for bridge engineers to determine the vibration-based deterioration or to remotely monitor the bridge bearing health, since it is obvious that typical bridge bearing damage appears nearly at resonant frequencies of the bearings.*

1 INTRODUCTION

Bridge bearings also called isolators are extensively utilised in bridge engineering. Since 1950s, they have been employed as thermal expansion isolators for highway bridges and seismic base isolation bearings for building applications, especially extreme acoustic environments. Bridge bearings are critical part of the bridge elements in a bridge system. According to a review in [1, 2], the isolation system using these bearings are able to provide an element with high stiffness in one direction and high flexibility in one or more perpendicular directions. Also, the key functions of bearings for building and bridge applications are not only to transmit and accommodate loads and lateral deformations between the superstructure and the superstructure of a bridge, but also they support the weight of the superstructure [3]. Besides, bearings used for bridge application purposes should be more considered in design than those used for building application, due to additionally rotational deformations induced by girders [4].

The concept of combining horizontal flexibility and vertical stiffness is strongly suggested to be used in design of typical bridge bearings [2]. For example, these common bearings consist of rubber pads laminated with reinforcement materials (i.e. steel plates). Over decades, the development of a novel design of bridge bearings with fibre reinforcement has been widely researched. Compared to bridge bearings reinforced by steel-reinforced bearings are relatively heavy because of the steel reinforcement plates [5]. Additionally, the cost of these bearings is high due to the labour severe fabrication process [5]. Therefore, the benefits of utilising fibre reinforcement in bridge bearings are simplicity of installation, lightweight, better damping properties, high base isolation performance and lower stresses in rubber and fibre layers [6].

A main element of a rubber bearing is the rubber pads, based on an investigation in [7]. They can be employed straight without being reinforced (e.g. plain rubber isolators), or the pads can be laminated with reinforcing materials, providing a high tensile capacity for rising the vertical stiffness of the bearing by dominating buckling of the rubber [3]. A review in [8], Caltrans stated that for the entire structure, the selection of seismic rubber isolators with reinforced materials is dependent on the preferred type of an isolator.

According to [2], a rubber bridge isolator can be sensitive to a buckling type of instability identical to that of a common column, but controlled by the low-shear stiffness of an isolator. Reviews in [9, 10], bridge bearings should have adequately vertical stiffness to transfer service loads and besides be capable to facilitate the horizontal or rotational movements occurred in the girders. The bearings having adequate stiffness in vertical direction can well perform to limit the buckling behaviour and also can reduce the risk of leading to accelerated bridge failure to the bridge structure [11]. For instance, damage is not allowed in bridge bearing under any expected actions [3].

One of the most common causes of bridge failure is the resonance phenomenon under highly various vibrations. It is vital to comprehend the modal characteristics of structural bridge elements for designing and to predict the vibrated behaviours of the bridge elements. In terms of general bridge bearings, they should be developed for preventing possibly the resonance by using complex structures to reduce vibration. More recently, the use of metamaterials consisting of metastructures has a great momentum for many applications. Based on studies in [12, 13] a common material having positive Poisson's ratio, PR shows a special situation of swelling in perpendicular to compressive loading. On the other hand, a metamaterial with negative PR exhibits shrink behaviour in a direction transverse to the direction of compression [14, 15]. Negative PR metamaterials express better mechanical properties and application prospects regarding lightweight [16], indentation resistance [17], vibration attenuation [18, 19], impact resistance [20, 21], and energy absorption [22, 23].

Our simulation shown in the following chapter was inspired by the development of typical bridge bearings using metastructures under dynamic condition which obtain superior modal properties. Nevertheless, there is no study in the comprehensively numerical modal analysis of novel bridge bearings in free oscillation. This study highlights the outcomes of a sensitivity investigation of free oscillation characteristics of a novel bridge bearing. The simulation of the bearing was investigated dependent on the finite elements, employing Fusion 360 software. The insight into dynamic will be useful for the study on non-destructive testing (NDT) and health monitoring of bridge bearings.

2 THEORETICAL BACKGROUND OF MODAL ANALYSIS

One of the most approaches to determine the dynamic properties of systems in the frequency domain is the modal analysis. In this study, the main objective is to identify the dynamic properties of novel bridge bearing components in terms of fundamental frequencies and mode shapes through the finite element method. The formulas of motion for free vibrations of a bridge bearing can be shown as follows [24-26].

In a dynamic network, the formula of motion of the network can commonly be denoted by:

$$[M]\{\ddot{y}\} + [D]\{\dot{y}\} + [S]\{y\} = \{q\} \tag{1}$$

Where [M] expresses the mass matrix, [D] represents the damping matrix, and [S] denotes the stiffness matrix. The harmonic load applied to the network with magnitude, Q and loading frequency ω is indicated by:

$$\{Q\} = Qsin(\omega t) = Qe^{j\omega t} \tag{2}$$

To be noted, a non-trivial solution to Formula (1) is $\{y\} = \{Y\}e^{j\omega t}$. Substituting the previous solution to Formula (1) and manipulating it with Formula (2), the formula of vibration is obtained as follows:

$$(-\omega^2[M] + j\omega[D] + [S])\{Y\} = \{Q\} \tag{3}$$

With some manipulations, converting Formula (3) employing modal coordinates by employing $\{Y\} = [\Phi]\{W\}$ and the orthogonality principle, and it later yields

$$W_i = \frac{\{\phi_i{}^T\}}{\omega_i^2 - \omega^2 + 2\zeta_i\omega_i\omega j})\{Q\} \tag{4}$$

Recalling $\{Y\} = [\Phi]\{\mathrm{W}\} = W_1\emptyset_1 + \cdots + W_n\emptyset_n$, Formula (4) can be re-written as presented by:

$$\{Y\} = \left(\sum_{i=1}^{n} \frac{\emptyset_i\emptyset_i^T}{\omega_i^2 - \omega^2 + 2\zeta_i\omega_i\omega j}\right)\{Q\} \tag{5}$$

Later, the reacceptance of the network can be determined by:

$$V_{ij}(\omega) = \frac{Y(\omega)}{Q_i(\omega)} = \sum_{i=1}^{n} \frac{\emptyset_i \emptyset_i^T}{\omega_i^2 - \omega^2 + 2\zeta_i \omega_i \omega j} \quad (6)$$

Therefore, ω_i is the resonant frequency, $\emptyset_i$ denotes the mass-normalized mode shape, and ζ_i denotes the modal damping ratio.

In terms of viscous damping (with critical damping c_r), $\zeta_i = \frac{d_i}{d_r}$; for proportional damping $([D] = z[M] + x[S]), \zeta_i = \frac{z}{2\omega_i} + \frac{x\omega_i}{2}$; and for hysteretic damping (η_i), $\zeta_i = \frac{\eta_{i\,i}}{2}$

3 A FINITE-ELEMENT SIMULATION OF NOVEL BRIDGE BEARING

The dynamic finite element (FE) simulation of a novel bridge bearing in free vibration was developed to investigate its dynamic response (i.e. natural frequency and mode shape). The FE model was generated in Fusion 360 software, using 3.72E+06 linear tetrahedral components with 5.71E+06 nodes. In this paper, we also focus on the free vibration of our model both free-free and fixed boundary condition. In terms of free-free boundary conditions, no excitation force was applied to the model, whilst the upper and lower surface of the model are not fixed because of free-free condition. For fixed condition, it is similar to the free-free condition, but the lower surface of the model is fixed.

Figure 1 demonstrates the three-dimensional finite element model for a novel bridge bearing. The honeycomb structure inspired us to create the engineered model. This is because a honeycomb structure gives a material with a very low density and relatively extreme out-of-plane compressive and out-of-plane shear performance [27-31]. The material and dimensions of the model geometry are based on the STANDARD DRAWINGS for Thai highway design and construction [32]. As given in Table 1, it indicates the material and geometrical properties of the FE model. A range of natural frequency investigations was carried out to evaluate the standard of the FE simulation. It is significant to note that the material utilised in this simulation is merely nitrile rubber, thus it is strongly suggested to use composite materials for this model, in order to acquire superior mechanical properties. Obviously, these components acting a bridge bearing can provide an expected estimation of bridge bearing's vibration in free-free and fixed condition. However, this model should be verified with experimental data in further research for public use in the near future.

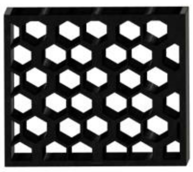


Figure 1: Finite element model of a novel bridge bearing in the free-free and fixed condition.

Parameters		
Material	Rubber	-
Elastic modulus	2	MPa
Poisson's ratio	0.49	-
Density	1.2E-06	kg/mm3
Model weight	5.12	kg
Model volume	4.26E+06	mm3
Model length	300.00	mm

Model width	300.00	mm
Model height	250.00	mm

Table 1: Engineering properties employed in the dynamic simulation.

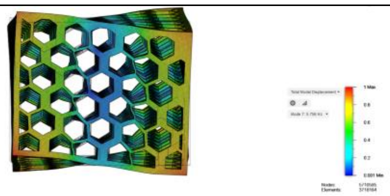
4 RESULTS

The outcomes of numerical modal analysis for the novel bridge bearing are shown in Table 2 and Table 3 for free-free condition and fixed condition, respectively. For the two bridge bearing models under free vibration with different boundary conditions, it was observed that the fist twisting mode in vertical plane certainly controlled the first resonant mode of oscillation in free-free condition. Whilst appearing the first rolling mode for fixed conditions. For a free-free condition, the first five modes of free vibrations are shown in Table 2. Surprisingly, the minimum harmonic corresponded to the fundamental twisting mode, the second harmonic to the first rolling mode, the third harmonic to the second rolling mode, the fourth harmonic to the first shrinking mode, and lastly the fifth mode to the first buckling mode.

However, it is different to the modes of vibration which were obtained for the bearing model in the fixed condition. Table 3 exhibits the first five modes of free vibration in fixed condition. Surprisingly, the minimum harmonic corresponded to the fundamental rolling mode, the second harmonic to the first torsional mode, the third harmonic to the first shrinking mode, the fourth harmonic to the second shrinking mode, and finally the fifth mode to the third shrinking mode. The most dramatic change in fundamental harmonic between the free-free and fixed condition was the second rolling mode in free-free condition, but the first rolling mode in fixed condition, respectively. The highest frequency decrease was approximately 47.36 percent. It is clear that the fixed support played an important role in decreasing the frequency values of all vibration modes, except the twisting mode due to the increase in the frequency values. In addition, it resulted in all the different mode shapes, especially for the lowest fundamental frequency when compared to free-free condition.

According to a mention in [33], the effect of free vibration, there are several factors affecting the natural harmonics and mode shapes, which are the mass, shape, constraint, stiffness, and applied tensile or compressive loads of material and structure.

On the other hand, the validation of this simulation should be conducted by a comparison between experimental data and numerical results, in order to obtain the improved model and to be safely used in public. It is significant to note that these results are highlighted the dynamic properties because of a development in health monitoring of bridge bearing elements which one typically measures the dynamic behaviours in the bridge system by accelerometers on the bridge bearing surface [34].

Mode no.	Mode shape	Natural frequency (Hz)	Behaviour
1		5.756	Twisting

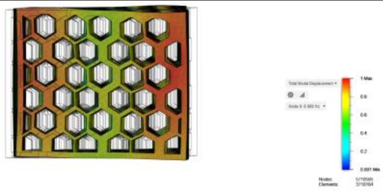
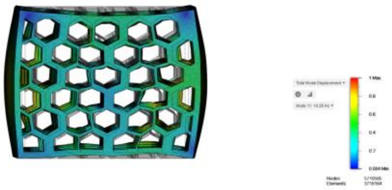
2		6.996	Rolling
3		8.308	Rolling
4		10.110	Shrinking
5		10.280	Buckling

Table 2: Natural frequencies of a conceptually novel bridge bearing (Hz) under the free vibration condition with free-free boundary condition.

Mode no.	Mode shape	Natural frequency (Hz)	Behaviour
1		4.373	Rolling
2		7.528	Twisting
3		7.973	Shrinking

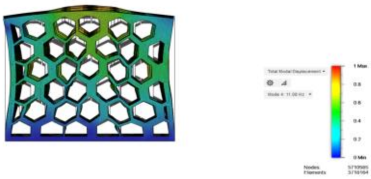
4		11.080	Shrinking
5		12.120	Shrinking

Table 3: Natural frequencies of a conceptually novel bridge bearing (Hz) under the free vibration condition with fixed boundary condition at the bottom surface.

5 CONCLUSION

Vibration characteristics of a novel bridge bearing play a major role in developing the realistic dynamic simulation of the bearing able to predict its dynamic response. The modal parameters of a novel bridge bearing in bridge system were investigated for modal analysis under free vibration with two different boundary conditions, through the finite element method using 360 Fusion software. The three-dimensional model using a honeycomb structure provides good mechanical properties and lightweight. Obviously, the resonant frequencies connected with the lower mode of oscillation of novel bridge bearing were dramatically influenced by the support boundary condition. Additionally, the mode shapes, which can behave the damaged condition of the novel bridge bearing, were affected by the fixed condition. To sum up, the fixed boundary condition had a particular effect on the vibration mode shapes and natural frequencies of a novel bridge bearing, particularly in the low frequency range. It is suggested that the determined modal parameters of the novel bridge bearing components were utilised to model bridge bearings where the influence of the boundary condition will be calculated. Nevertheless, the model should be created from composite materials that can provide superior mechanical properties. Furthermore, additional research for experiments of the novel bridge bearing fabricated by an additive manufacturing approach should be performed to compare the results between simulation and experiment.

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