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Analytical Study on Effect of Loosening on Nonlinear Vibration Behavior of Bolted Joints

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ABSTRACT: Bolt connections often loosen under environmental loading conditions and system vibrations, which can lead to disaster risks during its operation. In this study, the nonlinear vibration behavior of an aluminum single-lap joint has been studied analytically and experimentally. Accordingly, considering the effects of nonlinear behavior at the bole joint, a nonlinear two-degree of freedom model for this type of connection is proposed. Then, in order to determine the unknown parameters of the proposed model, the vibrational and dynamic properties of this structure have been estimated using experimental modal analysis and model updating method. Finally, the effect of the amplitude of the excitation force and the preload force of the bolts on the dynamic behavior of these systems has been studied analytically. Examination of amplitude-frequency curves shows that reducing the preload force of the bolts reduces the natural frequency and also distorts the amplitude-frequency curve to the left side, which indicates the softening nonlinear behavior of the system with decreasing applied bolt preload force. In addition, the comparison of the theoretical and experimental natural frequencies shows that the proposed model predicts the vibrational characteristics of these systems with good accuracy, and using the proposed model can study the dynamic behavior of these systems for different parameters.

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1. INTRODUCTION

The study of the vibration behavior of bolted joints has a special place due to their wide applications in various industries such as connecting different parts of aircraft fuselages, power plant towers, and missile tanks. Due to the fact that these structures are often under dynamic loads, so the probability of loosening and reduced quality of these connections is higher and if not detected in time, they can lead to breakdown and tragic damage [1]. Accordingly, the study of methods that can easily and accurately predict the dynamic behavior of bolted joints has been considered by many researchers. Accurate modeling to predict the dynamic behavior of structures is an essential tool in both design and operation [2].

Ahmadian and Jalali [3] have proposed a more general connection model for this type of connection using stiffness matrices and damping coefficients. They have proposed a method for identifying the optimal values of stiffness and damping parameters of a linear connection using the measured modal parameters. Gant et al. [4] used simple springs to simulate connection surfaces in the early stages of design. Zhao et al. [5] have proposed a method for identifying the dynamic parameters of the spring-damper element in bolt joints using modal properties. Evang et al. [6] presented an experimental study on the dynamic behavior of a single-bolt connection that withstands slips at different levels of torsion preloads and excitations.

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In the present study, a new method has been proposed to investigate the nonlinear vibrations of bolt joints of two aluminum sheets. To model changes in stiffness and local nonlinear damping at the bolted joints, a two-degree-of-freedom mass-spring-damper model is introduced. The parameters of the presented analytical model are obtained by using the model updating method and by means of the Firefly algorithm. Finally, for the first time, the problem of minimizing the objective function is formulated to minimize the difference between the natural frequencies of the analytical model and the results of experimental tests in the presence of the input constraint as a nonlinear optimization problem. The optimization process is solved using the firewall algorithm as a meta-innovative method to obtain the unknown parameters of the proposed analytical model. After determining the dynamic characteristics, using the proposed analytical model, the effect of various parameters such as preload and amplitude of external excitation force on the vibration behavior of this system has been studied. In order to validate the results, the system frequency changes for different values of the preload were compared with the results of the experimental test.

2. ANALYTICAL MODEL

Fig. 1 shows the geometric characteristics of the bolted joint sample. In order to study the dynamic behavior of the bolted joint presented in Fig. 1, the model is simulated using a nonlinear two-degree freedom system as shown in Fig. 2. Motion equations can be expressed in the form of the

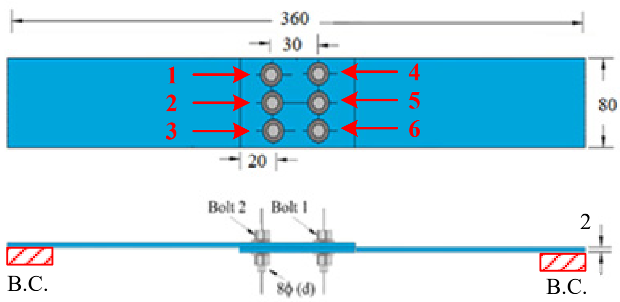

Fig. 1. Geometric characteristics of single-lap blot joint

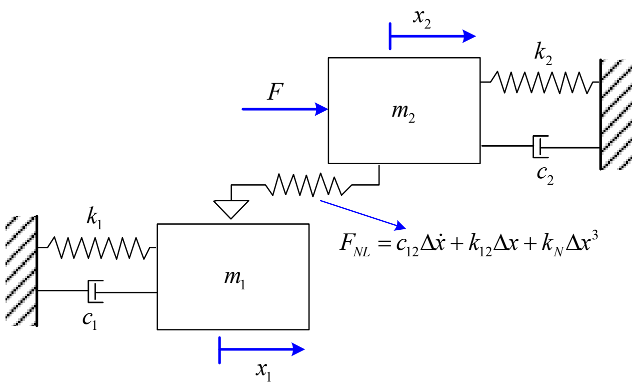

Fig. 2. Equivalent nonlinear two degrees of freedom model of the connection of single-lap blot joint

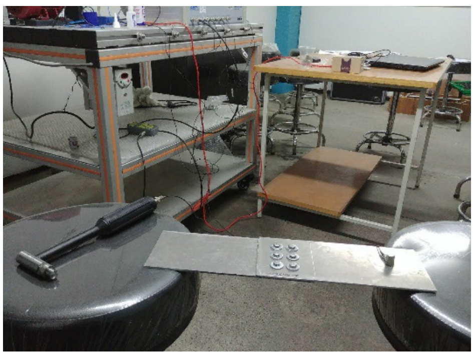

Fig. 3. Configuration of experimental test analysis of single-lap bolt joint

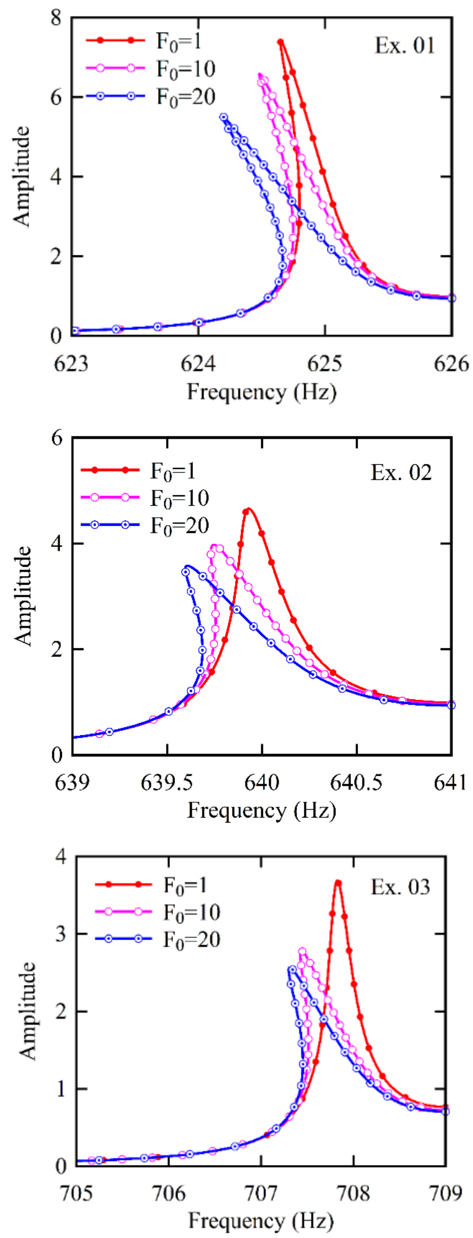

Fig. 4. Frequency response function curve obtained from the analytical model

following matrix:

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c + c_{12} & -c_{12} \\ -c_{12} & c + c_{12} \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k + k_{12} & -k_{12} \\ -k_{12} & k + k_{12} \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = \begin{Bmatrix} -k_N (x_1 - x_2)^3 \\ k_N (x_1 - x_2)^3 + F_{ext} \end{Bmatrix} \quad (1)$$

3. EXPERIMENTAL TESTS

As shown in Fig. 3, the laboratory equipment includes a pulse data collection system, B&K 2051 accelerometer, laptop, B&K 1087 impact hammer, and anti-noise cables.

For the initial values of variables, the natural frequencies of the system are calculated using Eq. (1), and then in each iteration of the optimization process, specific values are calculated and the value of the objective function is determined. The calculated value of the objective function is compared with the previous values. This process is repeated to minimize the objective function using the Firefly algorithm.

4. RESULTS AND DISCUSSION

In order to study the nonlinear behavior of bolted joints, the frequency response function curve for different values of the excitation force amplitude and around the first bending mode is shown in Fig. 4. The preload range of 1 N corresponds to the relatively linear response of the system. It can be seen that for example Ex.01 is generated for a significant deviation in the peak of the curve, but for other examples, this amplitude of excitation force has an ignorable effect on the deviation of the frequency response function and the behavior of these connections at high pre-loads. According to Fig. 4, it can be seen that for larger amounts of preload, the nonlinear behavior of the system intensifies, which is due to the looseness created in the connection and the creation of micro-slips. As the force range increases, the peak resonance point loses its symmetry and shifts to the left, indicating softening nonlinear behavior. It is observed that as the force amplitude increases, the frequency curves become narrower, indicating a decrease in the equivalent damping of the system. In addition, according to the results shown in Fig. 4, it can be seen that by increasing the preload of the bolt, the vibration behavior of these joints almost tends to the behavior of linear systems. The reason for this can be explained by the reduction of the effects of looseness between the joints during vibrations, which eliminates the effect of nonlinear factors.

5. CONCLUSIONS

In the present study, in order to increase the accuracy of modeling and to consider the nonlinear effects of bolt joints, a nonlinear two degrees of freedom equivalent to these joints was presented. After determining the equivalent dynamic characteristics, the effect of different parameters on the vibration characteristics of this type of connection was studied theoretically and experimentally.

Using the model updating method, the model parameters are predicted with appropriate accuracy and the model provides two degrees of precise freedom by which the dynamic behavior of the system can be studied with high accuracy. The model presented in this research with high accuracy and the need for the least computational time predicts nonlinear effects on the common surfaces of screw joints and can be easily applied to different types of joints in this field.

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