



EXPERIMENTAL ANALYSIS OF BOLT LOOSENING DYNAMICS CHARACTERISTIC IN A BEAM BY IMPACT TESTING

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ABSTRACT

Bolt joints are commonly used when joining two or more components together in mechanical structures due to its easiness to be assembled and disassembled for maintenance. However, self-loosening is one of the most frequently found as a cause of failure in dynamically loaded bolted connections. This paper discusses a simple way to observe the dynamic characteristic of a fixed-free beam that consists of two beams that connected by a single and double bolt. The tightening torque of the bolt is varied from loosening condition, 2.5 Nm, 5 Nm, 7.5 Nm, and 10 Nm. The dynamic characteristics of the beam are obtained by modal impact testing. The frequency response functions of the beam are observed to analyse the effect of looseness and tightening torque of the bolts to the dynamic characteristic of the beam. It is found that the loosening condition or lower tightening torque will shift the natural frequency of the structure. Significant change will be observed at the higher frequency. Moreover, the damping characteristic is also affected by changing the tightening torque. Especially, when loosening condition, the damping ratio becomes much higher than the tightening one. By this condition, the impact testing measurement could be applied as a simple way to monitor or detect the condition of bolted joint in a structure.

Keywords: bolt joint, loosening, impact testing, natural frequency, damping ratio.

INTRODUCTION

Mechanical structures consist of elements that are connected through some types of joints. Bolt joints are commonly used when joining two or more components together in mechanical structures due to its easiness to be assembled and disassembled for maintenance. However, stress cracking due to fatigue, self-loosening, shaking apart, slippage, and breaking due to corrosion is frequently found in bolted joint failures. After fatigue, self-loosening is the most frequent cause of failure of dynamically loaded bolted connections. Additionally, fatigue is often initiated by partial loosening [1]. Despite the importance of self-loosening in bolted connections, complete physical and mathematical models in explaining the bolt joint phenomena do not currently exist in the literature. Therefore, bolt loosening analysis and detection have become an important research area in mechanical engineering in efforts to prevent failures in a variety of mechanical applications.

Several methods of bolt modeling have been studied by some researchers. For instance, Ibrahim overviewed some dynamical phenomena and characteristic of bolted joint, including linear and nonlinear analysis [2]. Ahmadian proposed a non-linear generic element formulation for modeling bolted lap joints [3]. Bograd overviewed some approaches in modeling the dynamics of mechanical joints in assembled structures using the finite element method based on three different approaches: node-to-node contact using the Jenkins frictional model, thin layer elements, and zero thickness elements [4]. Adel presented a model for predicting the dynamic behavior of bolted joints in hybrid aluminum/composite structures by identifying the Young's modulus at the joint affected region. The proposed finite element model was verified by modal experimental data [5].

Furthermore, the experimental detection of the bolted joint loosening become an important activity in structural health monitoring to ensure the proper function and the safety of structures. Several methods have been developed regarding the detection of loosening in bolted joints, like using electrical conductivity measurement [6], piezo-ceramics actuator and sensor [7], vision-based detection using the Hough transform and support vector machines [8], and vibration and acoustic measurement and analysis.

Vibration and acoustic-based methods have been a common method to be developed in condition monitoring of a structure, including joint condition. Todd investigated the mode shapes of a simple beam based on varied bolted clamping force obtained from impact testing [9]. Ritdumrongkul used a PZT actuator-sensor in conjunction with a numerical model-based methodology to quantitatively detect damage of bolted joints [7]. The loosening of bolts can be quantitatively identified as the change in stiffness and damping at the bolted joint, indicating a high potential of this method in order to quantitatively monitor structural damage.

Furthermore, an application of a linear transducer array that generates ultrasonic beam using surface acoustic waves transmitted by was proposed. The bolt joint boundaries reflect surface acoustic waves and array elements receive the echo signals. The different tightening torques generated different acoustic intensity image [10]. Zhang identified bolt loosening and quantitative estimate of the residual torque, theoretically and experimentally, using two approaches in a comparative manner: a wave energy dissipation -based linear acoustic approach and a contact acoustic nonlinearity -based vibro-acoustic modulation method [11]. Moreover, a vibration testing to detect the bolted joint loosening system based on an



impulse response excited by laser ablation, which offers the potential to measure high frequency vibration responses on the structure [12].

This paper proposes a simple way to detect quantitatively the looseness of a bolt joint in a cantilever beam model by multi-input and single-output (SISO) modal impact testing. The purpose is to provide a very simple model that describes structure condition and characteristics with a single and double bolted connectivity, and it is not the intent to model specific local behaviors within the joint. The overall goal is to assess to first order, whether a vibration based modal analysis may be used to assess joints subject to simple connectivity (clamping force) loss where the connectivity is modeled by a simple non-linear stiffness function.

THE FIXED-FREE BEAM MODEL

The overall system to be modeled is two thin steel beams connected by single and two bolt and nut like shown in Figure-1. It is a modification of a fixed-free beam.

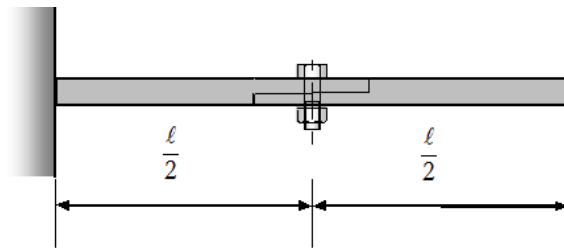


Figure-1. A fixed-free beam with bolted joint.

The equation governing free lateral vibrations of the beam is given by

$$m \frac{\partial^2 u}{\partial t^2} + \frac{\partial^2}{\partial x^2} \left(EI \frac{\partial^2 u}{\partial x^2} \right) = 0 \quad (1)$$

Where m , E , and I are mass/length, elasticity modulus, and inertia moment of cross-sectional area of the beam, respectively. In case of a bolted connection in Figure-1, the mass (m) and flexural stiffness (EI) are not uniform along the beam. The mass structure will increase by the mass of the bolt and nut, and the inertia moment (I) will decrease by different sectional inertia moment of the overlapped-connected beam, while the elasticity modulus E is constant for a linear model. The parameter $u(x,t)$ is the vertical displacement by beam length L . Equation-1 assumes that all properties are uniform along the beam. For a beam which its parts are joined and fastened by a bolt, the vibration equation becomes very complicated.

There are three types of contact used by researchers in this model. The first is bonded, where no sliding or separation between interfaces is allowed. The next is frictional, where two contacting interfaces may be subject to shear stresses up to a specified magnitude across the interface before sliding occurs. The last is no

separation, where a separation of the interfaces in contact is not allowed, but were small amounts of frictionless sliding may occur along the contacting interfaces [11].

These models of the contact interface will show that bolted joint analysis is a nonlinear analysis. The contact characteristics depend on the forces applied to the system, i.e., initial tightening torque and external working forces. As shown in Figure-2, the contact and friction forces depend on the external moment and clamping force to the bolt caused by tightening torque. Higher clamping force increases the stress contact area and the friction force in contact interface. Moreover, the higher external force will affect the friction resistance in the contact interface.

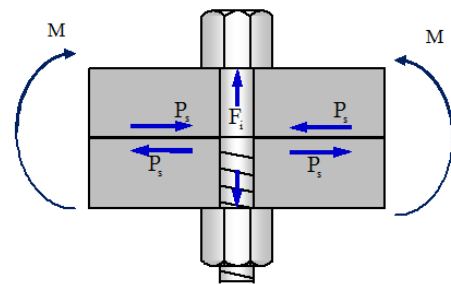
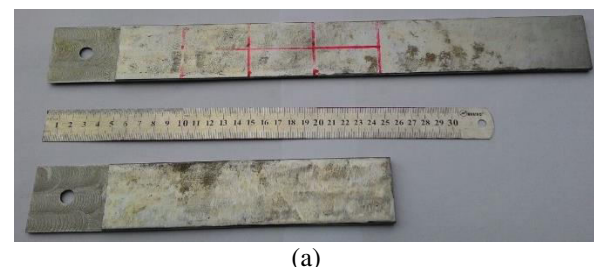


Figure-2. The simple model of forces working to bolted joint in flexural beam.

In this paper, the dynamic characteristics of the beam with bolt connection will be observed in various tightening torques. Two simple models of the fixed-free beam with bolt joint are used in this study. The beams that shown in Figure-3 are made of steel that connected by single and double steel M10 bolt. The dimension of the beams is 50 mm width and 6 mm thickness, and the total connected length of the beam is 450 mm. The overlapping part of the beams is machined to maintain the cross-sectional area uniform along the beam.



(a)



(b)

Figure-3. Two simple beam that will be joined by single bolt (a) and double bolts (b).



The experimental models in single and double bolt joint are illustrated in Figure-4. In the single bolt joint, the bolt position is in the middle of the beam and in the double bolt joint, the distance between the bolt is 50 mm. The bolts are tightened by various tightening torques; loosening condition (0 Nm), 2.5 Nm, 5 Nm, 7.5 Nm, and 10 Nm. The tightening torques are applied by a mechanical torque wrench for various torques and loosening conditions. For the double bolt, the tightening torques are also varied between two bolt, i.e. equal torque, and loosened-tightened bolt.

Impact modal testing is performed at each tightening torque level. The frequency response functions (accelerance FRF) then are obtained by single input-single output (SISO) measurement. The position of impact force and accelerometer is shown in Figure-4. Damping ratio is calculated by peak picking method in each frequency response peak. The result is discussed in the next chapter.

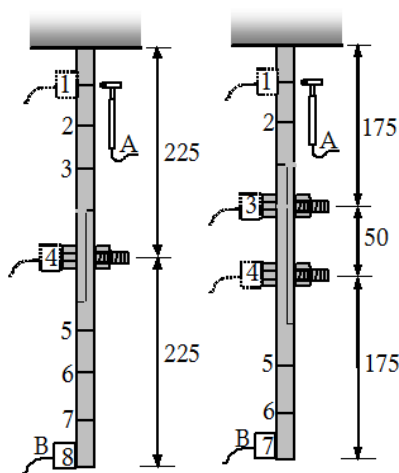


Figure-4. Experimental model with a single bolt (left) and double bolts (right), the length is in mm.

RESULT AND DISCUSSIONS

A plot of point frequency response of the beam with the single bolted connection is depicted in Figure-5. Various torques are applied to bolt joint. The graph in Figure-5 shows that the frequency response changed significantly at higher frequencies due to bolt loosening or tightening. Decreasing the tightening torque or totally loosening condition will shift the frequency peaks to the lower frequency. When the tightening torque is reduced, the resonance peaks in the frequency response shift to the lower frequencies. This change is significant at high frequencies, but it is not clear in lower frequencies. This is seen clearly when frequency responses are zoomed in lower frequency with different tightening torque from the higher torque to loosening conditions.

More details about frequency peaks are shown in Table-1. The natural frequency in the first mode is not shown having a significant change in different torque. The shifting of natural frequency is clearly observed in higher frequency mode, specifically in the 4th to 6th mode. It means that bolt loosening detection has become much

easier by evaluating high-frequency response because the significant peaks response shift in high frequency will be easy to be detected. This is clearly shown when a bolted joint is loosened, the stiffness of the joint is reduced, and the stiffness reduction leads the significant shift of the high-frequency resonance peaks to lower frequencies.

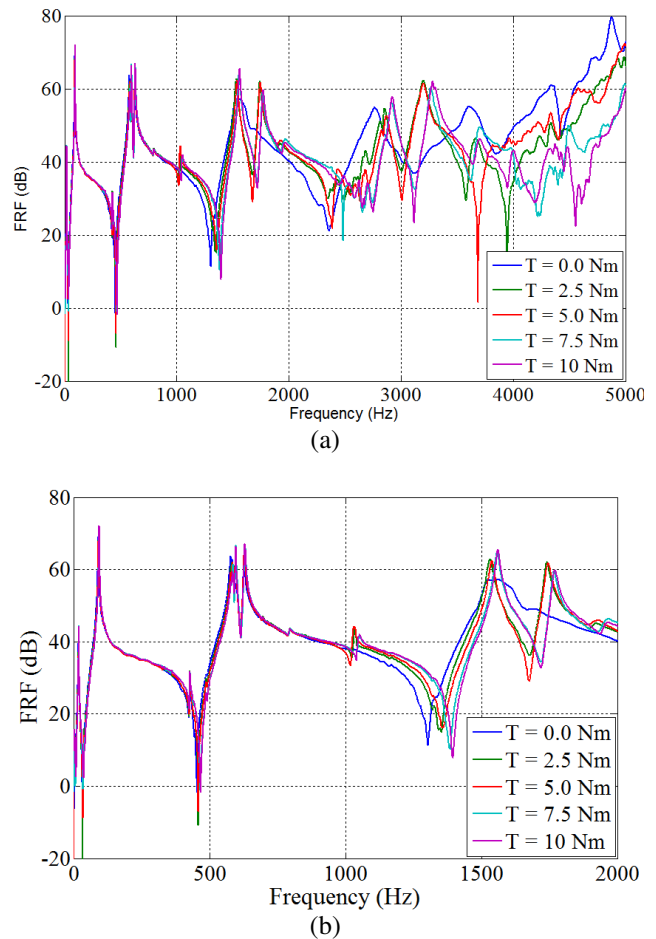


Figure-5. (a) Frequency response function of point 4-4 for various torque in single bolted joint, (b) zoomed at lower frequency.

Table-1. The Natural frequencies of uniform torsion single bolted.

Mode Number	Natural frequencies (Hz)				
	0.0 Nm	2.5 Nm	5.0 Nm	7.5 Nm	10 Nm
1	18,04	19,04	19,04	19,04	19,04
2	92,2	93,21	94,21	95,21	95,21
3	360,8	361,8	361,8	362,8	362,8
4	592,3	595,3	596,3	598,3	598,3
5	1026	1046	1046	1052	1052
6	1515	1523	1529	1548	1549

Furthermore, the resonance peak at low frequencies can also be considered using its vibration mode shapes. The principal vibration mode shapes of the single bolted joint model in various torques are shown in Figure-6. At the first mode in Figure-6a, the beam



undergoes a significant elastic deformation in loosening condition or at lower tightening torque. The increasing of elastic deformation is caused by decreasing the inertia moment of the cross-sectional area of the unclamped connected beam. When the tightening torque or the clamping force increases, the stiffness and the inertia moment will increase too. However, this phenomenon is not clearly shown in other vibration modes, like shown in Figure-6b.

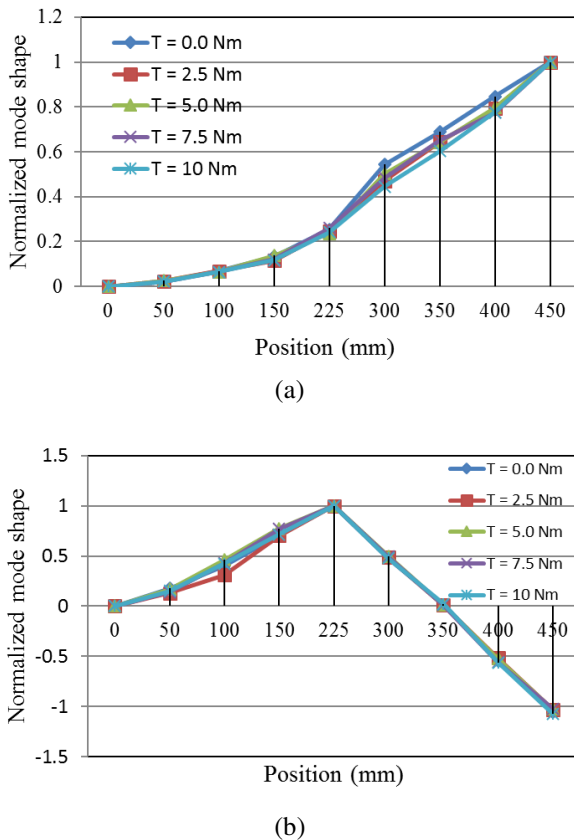


Figure-6. The mode shapes (a) the first mode, (b) the second mode.

Moreover, the effect of the looseness or tightening torque also is able to be observed by the damping ratio of the structure. Figure-7 describes the graphs of damping ratio as a function of tightening torque. The damping ratio increases by decreasing the torque. The beam with loosening condition has much higher damping ratio than tightened one, especially in the first mode. In loosening condition, the friction between two unclamped surfaces will absorb the vibration energy. Increasing the clamping force will increase the friction resistance between two surfaces. It needs more vibration force to make shearing motion between two surfaces. In this case, it is possible that the damping ratio does not depend only on clamp force, but affected also by vibration force.

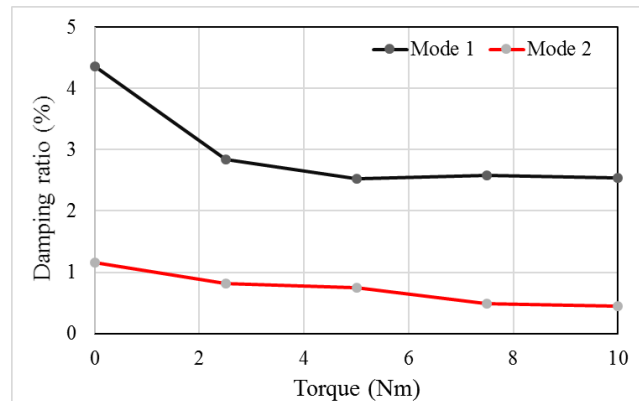


Figure-7. The damping ratio in various torsion of single bolted joint.

A similar experimental process is applied to the beam with double bolt joint. The plots of point frequency responses of the beam with various tightening torques for both bolts are depicted in Figure-8. The same torques are applied to both bolts. The graph in Figure-8 shows that the frequency response changed significantly at higher frequencies due to bolt loosening or tightening. Decreasing the tightening torque or totally loosening condition will shift the frequency peaks to the lower frequency. More significant frequency shifting occurs in double bolt joint rather than the single bolt joint. More details about frequency peaks are shown in Table-2. The natural frequency in the first mode has no significant change in different torque. The shifting of natural frequency is clearly observed in higher frequency mode, specifically in the 2nd to the 6th mode.

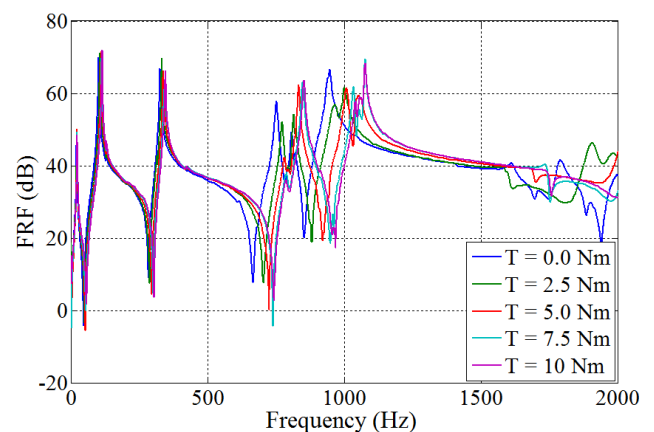


Figure-8. Frequency response function of point 4-4 for various uniform torsion in double bolted joint.



Table-2. The natural frequencies of uniform torsion double bolted.

Mode Number	Natural frequencies (Hz)				
	0.0 Nm	2.5 Nm	5.0 Nm	7.5 Nm	10 Nm
1	22,05	22,05	23,05	23,05	23,05
2	102,2	107,2	111,2	114,3	115,3
3	327,7	333,7	339,8	344,8	345,8
4	747,7	769,7	831,8	844,9	847,9
5	948,1	956,1	1007	1058	1073
6	1409	1588	1703	1756	1761
7	1737	1872	1992	2042	2060

Moreover, the effect of the looseness or tightening torque also is able to be observed by the damping ratio of the structure. Figure-9 describes the graphs of damping ratio as the function of tightening torque. The damping ratio increases by decreasing the torque. The beam with loosening condition has much higher damping ratio than tightened one, especially in the first mode.

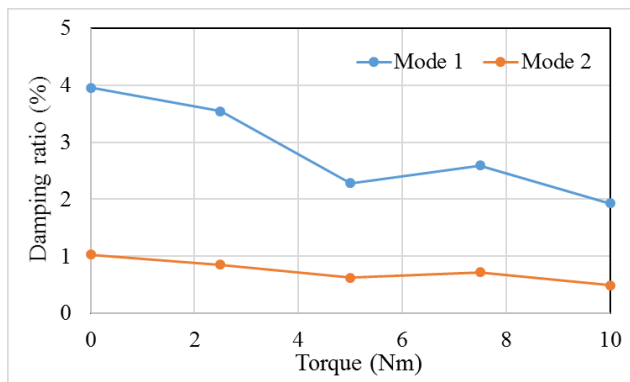


Figure-9. The damping ratio of various torsion in double bolted joint.

Then when the first bolt let in loosening and various torque is applied to the second bolt, the frequency response function is depicted in Figure-10. The graph in Figure-10 shows that the frequency response changed significantly at higher frequencies due to bolt loosening or tightening. The shifting condition is more than single bolted joint, but less than the equal torque one.

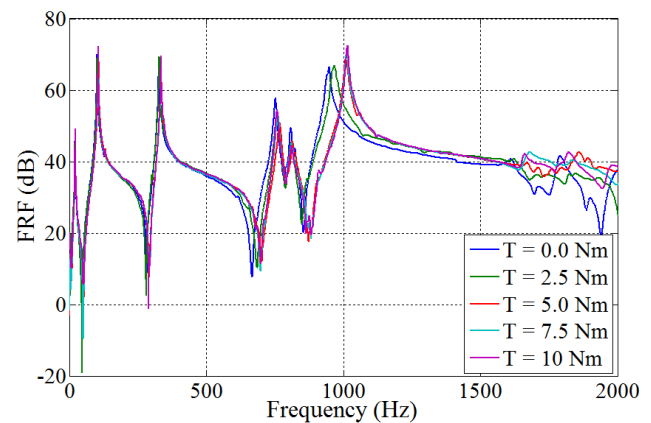


Figure-10. Frequency response function of point 4-4 for various different torsion in double bolted joint.

CONCLUSIONS

In this paper, the analysis of dynamics characteristic of the fixed-free beam with single and double connected beam has been done. The impact force is applied in the vertical direction to excite bending vibration of the beam. The various tightening torques are applied to the bolt joint, from the loosening condition to a maximum of 10 Nm torque. It is found the loosening condition or lower tightening torque will shift the natural frequency of the structure. Significant change will occur at the higher frequency.

Moreover, the damping ratio will increase by decreasing the clamping force, especially when loosening condition, the damping ratio becomes much higher than the tightening one. In some condition, the change also occurs in mode shape; more elastic deformation is observed in loosening or lower tightening torque. However, this phenomenon is not clearly shown. By this condition, this impact testing measurement could be applied as a simple way to monitor or detect the condition of bolted joint in a structure. Decreasing the natural frequencies or increasing the damping ratio became a symptom of the loosening or reducing the tightening torque of a joint.

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