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A Review Paper on Looseness Detection Methods in Bolted Structures

Abstract

Bolted structures are widely utilized in industrial structures and equipment due to the numerous advantages they possess. However, the use of bolts in these structures by itself can cause considerable flaws or damages. One of the major reasons of flaw in such structures is looseness. Since the looseness is initiated with a reduction in the axial force, measurement and estimation of this force can contribute to a healthy performance of the structure. The methods used to measure axial force of bolts are divided into two: those which measure or estimate the force directly and those which, by controlling physical parameters, do this indirectly. Ba- sed on this categorization, this paper examines over 16 methods used for evaluation of axial force of bolted structures, and presents their theoretical bases, drawbacks and advantages, with the litera- ture on each method being discussed separately. Finally, the met- hods are compared and the most important criteria in selecting the methods are introduced.

Keywords

Bolted Structures, Looseness Detection, Bolt Preload, Fault Detection, Ultrasonics.

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1 INTRODUCTION

Bolts are temporary connections and due to this feature, they are often used in most mechanical structures. Bolts possess several significantly favorable features like the ability to bear relatively heavy loads, low costs, easy installation and implementation and acceptable reliability. Besides the positive features, bolted joints are subject to flaw, which can consequently result in damages to the construction or equipment. The causes for such flaws include stress concentration, crack, corrosion and looseness. Looseness is a process initiated with slipping. Slipping, which can be caused by external forces or vibration, first occurs in bolt threads and plates and leads to slipping of the plates

and bolt heads, resulting in micro-vibrations of the plates (Bickford, 2007; Caccese, et al., 2004; Wang, et al., 2013; Hess, 1988).

Another problem with monitoring bolted joins in terms of looseness is assuring the appropriateness of the axial force applied to the bolt. As inadequacy of this force can cause damages to the structure due to looseness, excessive axial force could also impose stresses on the bolt, which in turn lowers its efficiency. Therefore, monitoring this axial force is a significant factor in detection and investigation of looseness of bolted joints (J. Bickford, 2008). To measure axial force and its adequacy or inadequacy, numerous methods exist, which could be classified under various groups based on the available literature. The basis for such classifications could include directness or indirectness of measurement, activeness or passiveness or even usage for online or offline condition monitoring. In this paper, the classification will be based on the directness or indirectness of the measurement method. In the former case, there are methods which measure axial force or bolt torque directly, while in the latter group, there exist methods which rely on physical phenomena and estimate looseness of joints using indirect strategies like parameters apart from axial force or screw torque. To do so, 16 disparate methods will be investigated and their usage instructions, drawbacks and advantages will be elucidated, together with the relevant literature.

2 DIRECT MEASUREMENT METHODS

Two important parameters in detection and assessment of looseness of bolted structures are the applied torque and the axial force on the bolts. Thus, to monitor the conditions of the joints, direct measurement of these parameters is a principal approach among the primary methods proposed and developed for such purposes. Although most of these measurement methods are old-fashioned and they are only mentioned in standard statements–and not in recent academic papers–they are still widely used in various industries (Goodier, 1945). As of now, various methods have been proposed for measurement of axial force, torque, torque control and rotation angle of screws and bolts. In the following section, the most important and practical direct axial force measurement methods will be presented.

2.1 Direct Tension Indicator Method

As shown in Figure 1, the axial force is measured using washers with protruding features on. The washers can be put either under the bolt or under the nut. Each washer is designed for a specific joint and unique purpose, meaning it has a particular function. With an increase in axial force, the gap between the features on the washer and the bolt (or nut) is decreased. A degree of compression is already expected for the features on the washer and when this is achieved, the axial force reaches the favorable degree. The advantage of this method is its straightforward installation and usage, while its disadvantage is the need for washers that are specifically designed for every particular joint. Besides, neither estimation of looseness is possible with this method nor online observation of joint conditions. According to previous research studies, if this method is utilized for parallel or dissimilar joints, estimation errors of 4 to 12 percent or 11 to 23 percent are expected respectively (Goodier, 1945; Sauer, 1950; Hong & Kim, 2009; Struik, et al., 1973).

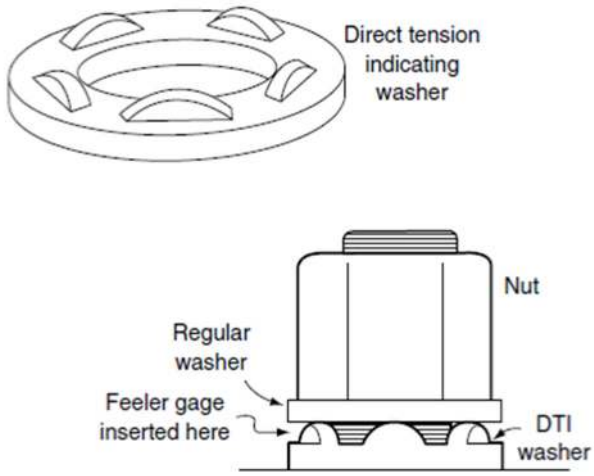


Figure 1: Direct Tension Indicators (Bickford, 2007).

2.2 Strain Gauges

Strain gauges or force sensors which are often electronic or piezoelectric are generally used in two ways: either as a washer or integrated bolts. Washer-like strain gauges are flexible rings which are placed between a given plate and bolt and measure the amount of pressure applied by the bolt. Once the torque is applied on the bolt, the axial force to the joint increases and the washer measures the applied force continuously. While these washers have acceptable accuracy, they are comparatively expensive and are mainly used for experiments and special cases. With the developments in technology, an ever-increasing number of manufacturers are producing integrated strain gauges and bolts (Figure 2). This, not only, results in elimination of washers and a reduction in the volume of joints, but it also reduces the force error by 1 to 2 per cent. Furthermore, in cases where several strain gauges are used in different points, bending and torsion can be detected as well (Goodier, 1945; Bickford, 2007).



Figure 2: A sample bolt with electrical strain gauge.

Another way is to use strain gauges to monitor length variations in bolts in order to determine the existing axial force in the joint. In this method, by installing strain gauges in both sides of a given bolt, the length variations in the bolt can be monitored and consequently its axial force could be controlled. The main drawback of this method is that because of the materials used in production of bolts, their strain is usually marginal and slight changes cannot be measured with high accuracy. Besides, this method can only be used when both sides of the bolt are accessible. In addition to this method, other methods such as those which use ultrasonic waves have been proposed and used for a more accurate monitoring of bolt length fluctuations, which will be delineated below (Goodier, 1945; Bickford, 2008).

2.3 Torque Control

One of the most primary methods to control and investigate looseness is the torque wrench technique. In this technique, using torque-meters, the inspector examines the torque of a bolt at determined time intervals and assures that it has not declined. While this method might seem old-fashioned, it is still used in many and various industries. Studies have shown that despite the simplicity and low cost of the method, only 10 to 15 per cent of the applied torque is used to spin the bolt, and 85 to 90 per cent is wasted to resist the existing friction, which results in significantly lower accuracy and up to 50 per cent of error. Although the use of lubricants can reduce the friction to a great extent, it can mean excessively more axial force, which may cause additional stresses on the structure. Apart from the mentioned drawbacks, this method does not allow for online monitoring of the structure, and its performance is dependent upon the inspector's performance, regular investigations and human errors, as well (J. Bickford, 2008; Goodier, 1945; Joshi & Pathare, 1984).

3 INDIRECT MEASUREMENT METHODS

As was mentioned above, despite their simplicity, direct methods have low rate of accuracy and they do not allow for online monitoring of bolted structures, and this has pushed detection and investigation methods toward indirect methods. In fact, in these methods, the effect of axial force reduction on a physical parameter is examined and using the variations and fluctuations of the parameter, the inadequacy of the axial force is estimated. In the following section, the most common types of indirect methods for detection and evaluation of looseness of bolted structures will be described, together with their merits and demerits (Joshi & Pathare, 1984).

3.1 Impedance Based Methods

Measuring impedance is an indirect method to diagnose and evaluate looseness. This method requires an impedance analyzer and a processor apart from the piezoelectric elements. The method is theoretically based on the fact that a system's impedance is a fixed value as long as it has the same state or condition. As the impedance of a system depends on dynamic features and parameters, every variation due to a flaw (e.g., crack, decay, corrosion, looseness, etc.) can affect the value of these parameters and cause a change in the impedance. Using these impedance fluctuations, it would be possible to diagnose and evaluate looseness of joints and to estimate the existing axial force in structures (S. J. Temitop, 2015; Liang, et al., 1994; S.Zhou, et al., 1995; Bhalla, 2004).

Two major approaches in this measurement method include the use of electrical impedance and electromechanical impedance. As shown in Figure 3, In this method, first piezoelectric transducers, which play the role of sensors as well as operators, are installed in specified points on the structure. In the electrical impedance measurement method, an electric pressure difference is applied on two sides of an electrode, and using an impedance analyzer, the level of electrical resistance (or impedance) is calculated based on the ratio of the voltage to the electric current in different frequencies. In the electromechanical impedance measurement method, the structure is stimulated with different piezoelectric elements and by analyzing the electromechanical response of the structure to the applied stimulation, the amount of impedance is determined using an impedance analyzer (Liang, et al., 1994; S.Zhou, et al., 1995; Annamdas & Soh, 2007; Overly, et al., 2007).

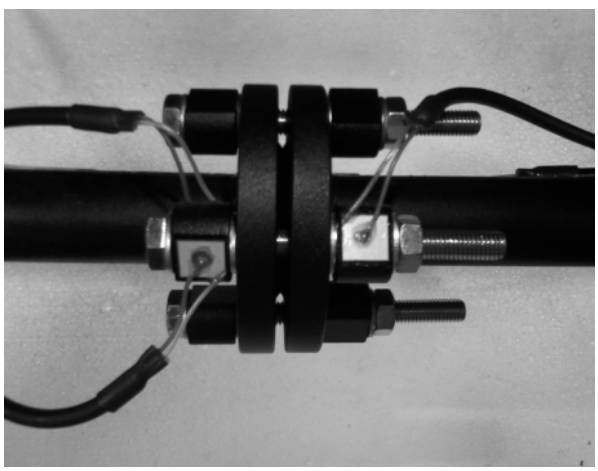


Figure 3: A sample section of a pipeline with electromechanical impedance test devices (Rosiek, et al., 2012).

The most salient feature of these methods is their high sensitivity to flaws, especially contact-related flaws. In fact, in such cases, the looseness of the structure has an impact on the firmness and attenuation of the joints and consequently on the impedance value of the structure. Besides, not only is this method used in troubleshooting of complex structures, but also due to its special function, it can be used in online monitoring of the conditions. Despite numerous advantages, this method has drawbacks, as well. The number of sensors and functions required for this method, especially in structures having a great number of bolts, is an unfavorable factor. Moreover, the method demonstrates unsatisfactory performance in systems with thermal fluctuations or loading (Annamdas & Soh, 2007; Huynh, et al., 2015).

The theoretical basis of this method were first proposed by Liang et al. (1994) and were then expanded by Zhou et al., Bhalla, Sou, and Anamandas, who proposed 2D and 3D models for dynamic interactions between a structure and its piezoelectric adapters (Krishnamurthy, et al., 1996; Pavelko, et al., 2014; Krishnamurthy, et al., 1996; Annamdas & S., 2007). In addition to the studies on modeling of this method, there have been other researchers who conducted studies on adequacy of this method in detection and evaluation of looseness of bolted structures. Ritdumrongkul et al., besides modeling the electrical impedance of a structure, studied the efficiency of the method empir-

ically, having a wave dispersal approach; while they provided indices to quantify the amount of looseness, they examined the sensitivity of indices to firmness and attenuation of joints (Ritdumrongkul, et al., 2004). Providing an index for evaluation of the looseness of bolts, Park et al. surveyed the efficiency of the method in detecting looseness in bolted joints of pipelines (Overly, et al., 2007; Park, et al., 2001). Pavelko et al. also conducted experiments on thin plates, and by investigating the effects of structure firmness, they described the mechanism of this method (Pavelko, et al., 2011). In addition to the conducted case studies, innovations have also been proposed in performing the experiments. Wait et al. proposed merging impedance measurement methods with lamb waves (Wait, et al., 2005) and An and Sohn (An & Sohn, 2012) asserted to improved efficiency of impedance measurements while using guided ultrasonic waves. Mascarenas et al. (Mascarenas, et al., 2009) suggested a new setup for impedance method which made use of wireless data-collection equipment.

3.2 Vibration Based Methods

Another indirect method for detection of looseness of bolted structures is analyzing vibration signals obtained from such joints and structures. As looseness results in reductions in firmness of joints and structures, its detection is possible if variations and fluctuations of the structure's vibration parameters are monitored. In these methods, it is assumed that a structure which suffers from looseness, emits nonlinear vibration responses due to the existence of flaws and changes in vibrational and dynamic parameters. Vibration application in this group of methods is performed through several ways, the most important of which is using hammers, vibrators or piezoelectric elements; the selection depends on the structure's size, work conditions and test costs. In this method, vibrational stimulation is carried out using one of the mentioned methods and the responses are recorded using a piezoelectric accelerometer or laser vibrometer. The received signals are then analyzed considering time, frequency, time-frequency or frequency-time to allow for detection of dynamic parameter changes due to the flaws (Tanner, et al., 2003; I. Milanese, 2008; He & Zhu, 2014; Feblil, et al., 2013; Sohn, et al., 2004).

The most important advantage of vibration-based methods is their theoretical and operational simplicity. For example, the impact test, using a hammer, could be performed with significantly more facility than the impedance test. Also, these methods are relatively more cost-efficient than other, for example ultrasonic, methods. However, despite such advantages, their principal drawback is that the obtained response from the experiments depends on the inspector or operator's experience. For instance, in the hammer method, the inspector touches the sides of the bolt with his/her fingers, strikes with a hammer and, using his/her intuition, determines looseness of the bolts based on nonlinear vibrations. Therefore, this method is expected to yield diverse results depending on the accuracy and experience of the inspector. On the other hand, if the joint vibration analysis is performed out of the experimental conditions where the signal analysis process is intended, it will demonstrate difficulties, especially in cases of geometrically complex structures. Besides, vibration-based methods (except for those in which piezoelectric elements are used), due to their function, lack the required potentials for online monitoring of conditions (J.H. Park, 2015; He & Zhu, 2014; Feblil, et al., 2013; Sohn, et al., 2004).



Figure 4: A steel pipeline with bolted flanges and the placement of the accelerometers (He & Zhu, 2014).

It was Junker (Junker, 1969) who studied the looseness mechanism of bolted structures theoretically and empirically for the first time in 1969. He illustrated that if the two bolted plates are subjected to a sectional vibration or if the external stimulation force can overcome the friction force, micro-vibrations and consequently the looseness process will begin. Later, Groper (Groper, 2009) demonstrated that the dynamic micro-vibrations which take place where threads are joined are different from micro-vibrations occurring between plates or joined parts in a bolted structure. Following this line of investigation, Pai and Hess (Pai & Hess, 2001) showed that in case of micro-vibrations at the beginning of the looseness process, there are three areas where vibrations take place which include the joints between threads, the joints between plates, and the joints between bolt heads and plates. However, the fact that bolted structures having looseness emit nonlinear vibrational responses was first proposed by Ungar (Ungar, 1973), which paved the way for the usage of vibration-based methods in detection and evaluation of looseness. In addition to this, Adams and Farrar (Adams & Farrar, 2002) also showed that in a flawed bolted structure under investigated, both linear and nonlinear response parameters undergo changes. Because of this, LuGre (Wit, et al., 1995), when carrying experiments on flawed bolted structures, concluded that to model micro-vibrations of such structures, nonlinear models should be employed. In addition to the conducted research on theoretical models and impacts of vibration on looseness of structures, various case studies have also been carried to evaluate the efficiency of vibration-based methods. Trendafilova and Van Brussel (Trendafilova & Brussel, 2001) and Tjahjowidodo et al. (Tjahjowidodo, et al., 2007) could detect backlash and looseness of bolts, analyzing the signals obtained from joint vibration of robots. Caccese et al. (Caccese, et al., 2004) studied the feasibility of detection and evaluations of flaws in composite bolted structures. Feenstra, et al. (Feenstra, et al., 2005) surveyed vibration responses obtained from the connections with small bolts empirically and using an analytical model – which took adhesion and slipping effects into account – and having performed validity in-

vestigations, proved the efficiency of the method. Guarino and Hamilton (Guarino & Hamilton, 2009) investigated the vibrational signals obtained from impacts to metal structures and Esmaeel et al. (Esmaeel, et al., 2012) and He and Zhu (He & Zhu, 2014) examined ways to diagnose and evaluate looseness of flange bolts in pipelines which a simple setup of their test is shown in Figure 4. Besides these studies, innovations have also been made by scholars regarding signal processing and analysis of vibrational signals. Nichols et al. (Nichols, 2007) obtained vibrational responses from a bolted structure and, using Fourier transform, extracted the linear response ratio of the vibrational signal. Subsequently, comparing the obtained response with the linear response, he estimated the amount of flaw in the structure. Milanese et al. (Milanese, et al., 2008) detected structure looseness via analyzing vibrational signals and investigating the frequency content of systems. Razi et al. (Razi, et al., 2013) used the empirical mode decomposition method to do so.

3.3 Ultrasonic Based Methods

Another set of methods used to monitor bolt conditions, which possess a high level of favorability, are ultrasonic-based methods. In this category of methods, the changes in the ultrasonic wave sent to a structure is examined as an index for the existence of flaw. The waves used in this category of methods could be longitudinal, transversal or surface and could be used either in pulse-echo or transmission methods. In the pulse-echo method, the piezoelectric sensor and actuator – which are often of PZT type – are placed at one side of the structure and they send and receive the ultrasonic waves. In the transmission method, the sensor and operator are placed at opposite poles of the structure and the wave is sent at one side and the response is received at the other side (Rose, 1999).

These methods investigate the ultrasonic signal which passes through the flawed structure by studying linear phenomena like reflection and scattering of the waves as well as nonlinear phenomena such as modulation of signals, energy wastage, etc. Among the proposed methods, according to research studies, the guided waves and lamb waves methods are two of the most practical ultrasonic stimulation methods. Guided waves are named so because their scattering is reliant upon the geometry of the structure, and the boundaries of the parts or of the structure help guide the waves in definite directions. The advantage of these waves is their ability to travel longer distances inside the structure and cover greater depth in the sample. Lamb waves are in fact a type of guided waves and they are used in troubleshooting of bolted structures. The difference is that their frequency range is dissimilar and they are often used to troubleshoot thinner structures (Rose, 1999; Meo & Amerini, 2011; Park, et al., 2015; Wang, et al., 2013; Joshi & Pathare, 1984; Alleyne & Cawley, 1992; Cawley & Alleyne, 1996; Cho, 2000; Raghavan & Cesnik, 2007; Park, et al., 2006).

As will be discussed later, there exist numerous methods to examine the changes in ultrasonic waves. Overall, the methods can be divided into three categories. The first category encompasses methods like those with active piezoelectric sensors which consider energy level fluctuations of the wave. The second group includes methods like flight time, velocity ratio and mechanical resonance frequency shift method which study wave frequency and velocity via a stress field (which is called the acoustoelastic effect). The third class is composed of methods, like second harmonic and side bands, which take into account higher and lower frequencies in the response frequency of the structure (Hong & Kim, 2009; Hess & Basava, 1998).

3.3.1 Piezo Active Sensing Method

As was mentioned, the amount of energy wastage of ultrasonic waves which are spread through the structure is considered as an index. Figure 2 displays the mechanism of this method. In this method, piezoelectric elements are attached to both sides of the bolted joint and the ultrasonic signals are sent via one and received through the other. As all the surfaces in structures and joins are rough, ultrasonic waves are always subject to wastage of energy. However, it should be noted that if the structure remains steady, the amount of energy wastage will be constant, too. In fact, in this method, the increase in energy wastage accounts for the change in structure conditions and therefore represents looseness of bolts.

The advantage of this method is its ability to allow for instantaneous monitoring of conditions due to its function. In addition to this, the frequency range used for stimulation purposes in this method is relatively low and as a result there will be no need for sampling equipment with high frequency, which leads to comparatively lower costs. However, in this method, if a structure with a great number of bolts is to be investigated, the high number of sensors, operators and connectors will result in an increase in the volume of test equipment and will probably incur higher costs (Wang, et al., 2013).

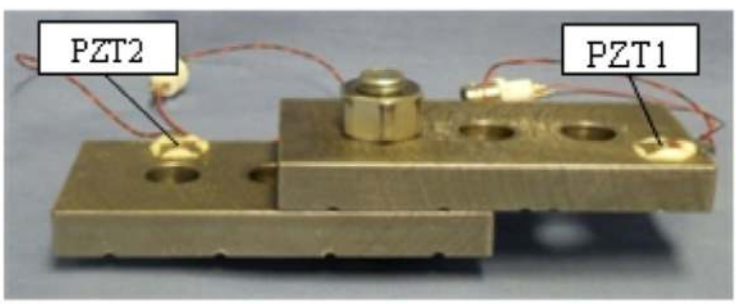


Figure 5: An example of the equipment used in the piezo active sensing method (Wang, et al., 2013).

Yang and Chang (Chang & Yang, 2006) claimed that their proposed method is not only able to detect backlash, but it also can determine torque area of bolts. As a matter of fact, their method was based on reducing the energy level of ultrasonic waves, which was later used as the theoretical basis for active piezoelectric sensing method. Some years later, Doyle et al. (Doyle, et al., 2010) examined the efficiency of this method empirically and it was Wang et al. (Wang, et al., 2013) who proposed the standard experimental setup which is shown in Figure 5 in 2013. The results indicated that increasing the torque area dramatically affects the amount of energy obtained by the second piezoelectric elements. The point is that this increase in torque will not always result in a rise in energy level and in fact if the amount of torque is increased beyond a certain level, the joint is saturated somehow; since all touching surfaces have a tendency toward real and flawless contact surfaces, the increase in torque level would not have a considerable impact on the obtained energy signal.

3.3.2 Acoustoelastic Effect Based Methods

Acoustoelastic effect is built upon the assumption that the velocity and frequency of scattered waves throughout the bolt is closely associated with the preload in it (Wang, et al., 2013). In this method, the ultrasonic wave is sent into the material and based on the variations made in transfer velocity or resonance frequency due to the acoustoelastic effect, the existing stress field in the structure is estimated. This method has numerous application in estimating residual stress field in welded steel plates (Salamanca & Bray, 1996; Tanala, et al., 1995), railways (Hirao, et al., 1994; Szelążek, 1992), rods (Chen, et al., 1998) and multi-wire stands (Chen & Wissawapaisal, 2002; Di-Scalea, et al., 2003; Kwun & K. A. Bartels, 1998; Rizzo, et al., 2003; Washer, et al., 2002). Another area of usage for acoustoelastic-based methods is their application in detection of the looseness degree of bolts and assuring the adequacy of axial force on joints (Chaki, et al., 2006; Chaki, 2007; Johnson, et al., 1996).

Three of the most important usages for this purpose include the time of flight method, velocity ratio method and mechanical resonance frequency method. These methods, as will be discussed in the following sections, measure preload of bolts using one of the following traits: (1) the transfer time of the ultrasonic wave throughout the bolt, (2) the ratio of transfer time of the longitudinal wave to ultrasonic transverse wave in the bolt, and (3) mechanical resonance frequency shift method in the bolt (Wang, et al., 2013).

Time of Flight Methods (TOF)

As was explained previously, according to the acoustoelastic effect, the stress field in a bolted structure can affect the scattering velocity of the wave inside the material. The theoretical basis of this method, as was mentioned above, is acoustoelastic. As shown in Figure 6, in this method, the piezoelectric element is stuck to one side of the bolt and the ultrasonic wave is sent into the segment in pulse-echo forms. This should be repeated both for stress-free joints and for joints which display stress due to the application of torque, with the flight time of the wave being measured each time. By recording the two times and using the overall relations which Kelly et al. and Johnson et al. used for homogenous and isotropic material, stress field and consequently the axial force of the joint can be calculated (Johnson, et al., 1996).

The main advantage of this method in addition to its simplicity and understandable theory is that due to its comparativeness, experimental conditions and environmental noises have minimum effect on the results. However, this method also has a noticeable downside, which is its inability to monitor the conditions online. In fact, in online troubleshooting, it is not possible to dismantle the structure form other parts and examine it in loose or flawless states. Furthermore, as the needed time for wave flight is in nanoseconds, the sampling rate to be used should be excessively high, which contributes to high costs of the equipment. Besides, this method takes into account the reflection phenomenon in the ultrasonic waves. This phenomenon is a linear phenomenon and compared to other methods which consider phenomena and nonlinear effects, has a lower level of accuracy (Heyman & Churn, 1992; Crecraft, 1967; Nikitina & Ostrovsky, 1998).

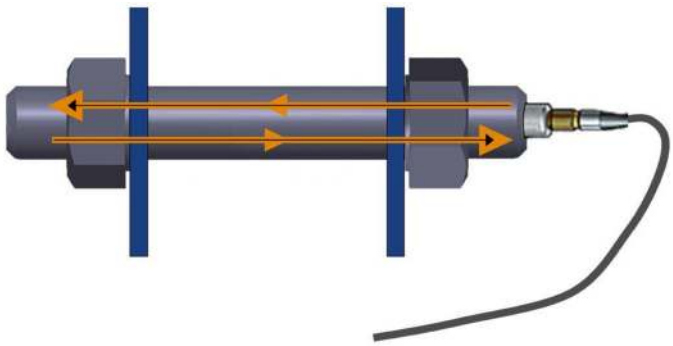


Figure 6: Schematic of TOF mechanism.

Velocity Ratio Method

As was mentioned, since in most cases, it is not possible to remove bolts and test them in a stress-free state, it is not practical to use the time of flight method. Because of this, the velocity ratio method was proposed, which can estimate the axial force of the structure using the ratio of flight time of longitudinal waves to transversal waves under stress conditions. The method functions like the previous one, with the difference being that there is no need to dissemble or assemble the bolted structure and access to one side of the bolt makes the test possible. In addition to the mentioned advantages for this method, unlike the previous one, it is not necessary to have the exact length of bolts and its theoretical relationships is independent of the length of bolts and flight time in stress-free states. However, like the previous method, its main disadvantage is that flight time ratio fluctuations of the transversal wave to the longitudinal wave are marginal and its measurement requires sampling equipment with high accuracy, which will mean more costs (Chaki, 2007; Johnson, et al., 1996).

Mechanical Resonance Frequency Shift Method

In a bolted structure, acoustic resonance frequency is a function of bolt length and wave propagation velocity. Furthermore, when a bolted structure is under stress due to application of torque, these two parameters are influenced because of the acoustoelastic effect. The mechanical resonance frequency shift method is built upon these two assumptions. In this method, by monitoring acoustic resonance frequency variations, it is possible to estimate the stress field and consequently the axial force of the joint. However, in this method, like the two previous ones, as the fluctuations of resonance frequency are slight, there is a need for sampling equipment with a measurement sensitivity in megahertz, and this implies significantly high costs (S. J. Temitop, 2015; Wang, et al., 2013; Nguyen, et al., 2011).

The methods which are based on the acoustoelastic effect were proposed by Conradi et al. (Conradi, et al., 1974) in 1974 for the first time. They used a transmission oscillator ultrasonic spectrometer (TOUS) to measure the acoustic resonance frequency changes in a bolted structure and examined the efficiency of the method in estimation of the axial force of the structure. Following them, Jeyman (Heyman, 1977) proposed reflection oscillator ultrasonic spectrometer (ROUS). His

experimental results suggested the existence of a linear relationship between the frequency transfer and the applied stress. Based on the pseudo-continuous wave technique, Joshi and Pathare (Joshi & Pathare, 1984) recommended the phase detection method to detect the amount of resonance frequency shift and approved of the linear relationship between the frequency transfer and the applied stress proposed by Jeyman. Later, Johnson et al. (Johnson, et al., 1996) in 1986 studied the efficiency of the velocity ratio method for the first time. Although at first, the accuracy of the empirical results obtained by them did not draw attentions, Yausi and Kawashima investigated the efficiency of the time of flight method and velocity ratio and gained more acceptable results using longitudinal and transversal waves with frequencies of 5 and 10 megahertz respectively (Kawashima & Yasui, 2000).

Hamdan et al. (Liew, et al., 2006) also did experiments on bolted joints in steel structures and obtained similar results for the time of flight method. In addition to the case studies conducted on methods which are based on the acoustoelastic effect, innovations have also been achieved and proposed in terms of test performance and signal analysis by scholars. Hirao et al. (Hirao, et al., 1994) used non-contacting shear-wave electromagnetic acoustic transducer (EMAT) in the time of flight method and they demonstrated that there is a linear relationship between the flight time and axial force of the structure. Jhang et al. (Jhang, et al., 2006) suggested a new method named phase detection method for precise measurements of flight time. They showed that the measurements of velocity fluctuations of the ultrasonic wave in the time of flight method, which is sensitive to the surrounding noises, requires extremely accurate equipment and high expenses; the phase detection method could reduce the costs significantly. Besides, the results obtained by their proposed method showed that there is a linear relationship between the increase in the stress in the structure and the decrease in wave velocity.

3.3.3 Methods Based on Emergence of Harmonics

To begin with, as will be explained, it should be noticed that there is a difference between the second harmonic method and side band method. In the second harmonic method, the stimulation signal is ultrasonic, while in the side band method, the system is simultaneously stimulated with vibrational and ultrasonic signals. Although both methods display similar results in terms of frequency, there are essential differences in various aspects, as will be explained below.

Second Harmonic Method

The emergence of higher harmonics is among the phenomena that is observed in signal analysis of structures. This phenomenon generally happens for two major reasons: presence of nonlinear effects in the material and/or presence of nonlinear effects in surfaces in contact. The flaws due to the first reason can be explained by the Hook Law and by considering nonlinear terms (Rokhlin, et al., 1981; Jhang, 2000; Barbieri, et al., 2009). However, in the case of flaws in bolted structures, the second reason is bolder.

When the ultrasonic wave hits the flaws causing nonlinear effects such as crack, delamination, or contact flaws like looseness of bolted structures, the nonlinear behavior of the set gives rise to a second harmonic in the frequency spectrum of the signal. This phenomenon has not only been fre-

quently observed empirically, but it also can be explained by contact acoustic nonlinearity (CAN) theories (Duke & Kiernan, 1988).

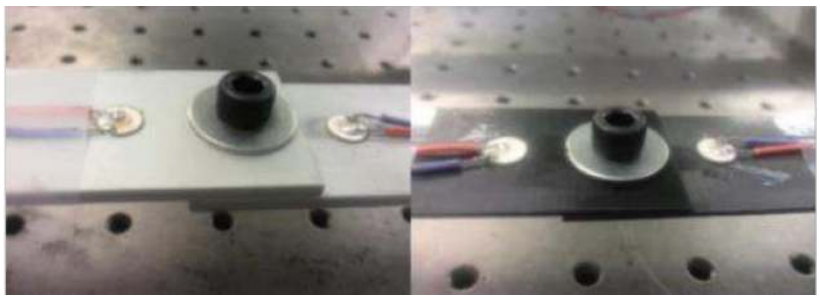


Figure 7: An example of experimental setup for second harmonic generation (Zhang, et al., 2016).

According to Figure 7 which show an example of experimental setup for second harmonic generation method, in this method, the ultrasonic wave enters the structure via either pulse-echo or transmission methods through the piezoelectric element and, while the wave passes the structure, the structure's response to this wave is obtained. If the axial force of the bolted structure is inadequate and the bolts are loose, the contact surfaces are not bolted firmly or flawlessly and the acoustic impedance is increased; hence, the second harmonic will appear in the response signal in the Fourier space. The bigger the range of the appeared harmonic, the worse the flaw in the joint (Hikata, et al., 1963; Kim, et al., 2006; Cantrell & Yost, 20001; Frouin, et al., 1999).

Side Band Methods

This group of methods is an integration of methods based on vibration and those based on ultrasonic. In general, in these methods, the vibration and ultrasonic signal enter the structure simultaneously and the presence of factors causing nonlinear effects like crack, delamination, looseness of bolts, etc. will cause modulation in the signals. The caused modulation in the frequency area will be represented as side bands components and an increase in the range of these components would mean an increase in the amount of flaw. Overall, these methods are divided into two groups based on the type of the vibrational stimulation: impact modulation and vibroacoustic modulation method. If the vibration signal is applied using a hammer, the method is called impact modulation and if a shaker is used for the stimulation, it is named vibroacoustic modulation. It should be noted that in both methods, piezoelectric elements are used to produce ultrasonic signals. The reception of the system's response signal can also be performed in different ways depending on the experimental conditions. The most important and practical ways include using piezoelectric, electromagnetic accelerometers and laser vibrometers (Polimeno, et al., 2008; Meo & Zumpano, 2005; Meo & Zumpano, 2007; Zumpano & Meo, 2008; Meo M, 2007; Polimeno & Meo, 2008; Kawashima, et al., 2006; Abeele, et al., 2000; Straka, et al., 2008; Donskoy, et al., 2001).

In this method, a vibration signal with low frequency and an ultrasonic signal with high frequency stimulate the system simultaneously. Since the passage of the ultrasonic wave through contact surfaces coincides with the vibration of the structure, the ultrasonic range experiences fluctuations due to the changes in dynamic characteristics of the structure. Because of this, as can be seen

in Figure 8, the response signals modulate each other in case of contact flaws like looseness of bolted structures. In such a condition, there will be side bands with integral multiple intervals from the vibration frequency around the ultrasonic frequency. In theoretical terms, the components have equal ranges, but the experimental results do not approve of this. After the reception of the modulated signals, the signal is analyzed. Given an index defined in order to investigate the amount of modulation, the amount of the index is measured for different applied torque values and the relationship between the amount of looseness of the structure and the value of the index is determined (Meo, 2011; Amerini, et al., 2010).

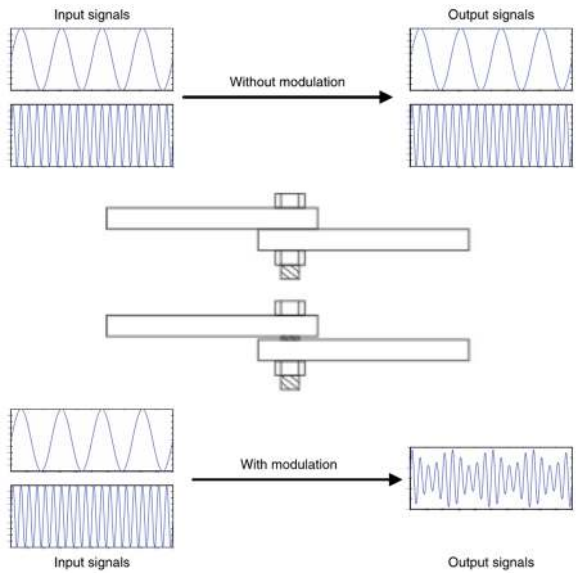


Figure 8: Modulation phenomenon for a loosening bolt (Meo & Amerini, 2011).

The main advantage of methods based on harmonics is their relatively high accuracy in comparison with other ultrasonic methods. As was mentioned above, ultrasonic methods are often based on linear phenomena like reflection, scattering, etc. which have lower accuracy compared to methods such as the side band one which are used for monitoring of nonlinear phenomena like modulation. Besides, if the performance vibration of the structure itself is used as vibration signals in the side band method, online monitoring of the structure would also be possible. The important point is that in this method, although there is a high level of accuracy and efficiency in detection of loosened structures, which is approved in detection and evaluation of other flaws in structures, no comprehensive reason has ever been proposed for the occurrence of modulation (Meo & Zumpano, 2005; Broda, et al., 2014).

While the side band method has proved its efficiency in detection of various flaws like crack, corrosion, decay, etc., and in theory it has proved to be useful in detection and evaluation of loosened bolted structures, it has received little attention in research studies in recent years. The most important studies are probably those conducted by Amerini et al. (Meo & Amerini, 2011; Amerini, et al., 2010) who investigated the efficiency of the vibro-acoustic modulation method in detection and evaluation of looseness in bolted structures. They used two plates with one bolt, and to quanti-

fy the amount of looseness, they utilized the hyperbolic tangent curve. Adams and Meyer (Meyer & Adams, 2015) also surveyed the efficiency of the impact modulation method theoretically and experimentally. They first proposed a theoretical model for looseness of two connected metal plates, then performed a troubleshooting by numerical simulations, and finally validated their model by comparing the results with experimental ones. An example of experimental setup for Impact Modulation method is shown in Figure 9.



Figure 9: An example of experimental setup for Impact modulation method (Jaques & Adams, 2011).

3.4 Other Indirect Methods

Apart from the proposed methods in the previous sections, there are other methods suggested by scholars which are capable of detecting and evaluating looseness in bolted structures. However, the methods have not been employed widely. These methods are described below.

Acoustic Moment Method

This method is a combination of ultrasonic and acoustic methods and its main advantage is that, like ultrasonic methods, it does not require a definite path for the movement of the wave. Besides, it has displayed acceptable efficiency in detection of looseness in heterogeneous materials. The major disadvantage of the method is that the obtained signals in this method are vague and they contain a great deal of noise. In fact, due to the presence of such noises, specific probes should be employed in this method, and this means a higher cost to perform the test (Kwon & Lee, 1999; Meo & Amerini, 2011). Alleyne and Cawley (Alleyne & Cawley, 1992) and Vary and Bowles (Vary & Bowles, 2004) were among the researchers who investigated the efficiency of this method in detecting flaws in bolted structures and showed that by measuring the acoustic moment of a bolted structure, a great deal of information could be obtained about the structure.

Image Processing Based Methods

As was mentioned above, one of the methods to estimate axial force of the joint is investigating the longitudinal fluctuation of the bolt. To do so, different direct and indirect methods like those which use strain gauges or ultrasonic waves have been proposed. Another set of methods used for such

purposes is methods based on image analysis. Image analysis is the process of using the computer to digitalize the image and detect the changes in the section or structure by comparing the images. This process includes five main steps: (1) taking photos of the structure using a digital camera, (2) preparing the images before the main analysis, (3) selecting the part of the picture to be analyzed, (4) extracting differences by comparing the images, and (5) interpreting the results from the previous step and detecting the flaws (Park, et al., 2015; Huang, et al., 2009). The efficiency of the method in detection of different flaws like cracks (Abdel-Qader & Kelly, 2003; Hutchinson & Chen, 2006; Yamaguchi & Hashimoto, 2010; Subirats, et al., 2006; Zou, et al., 2012), corrosions (Choi & Kim, 2005; Lee, et al., 2006) or even online monitoring of cable bridges (Ho, et al., 2013; Fukuda, et al., 2013) has been proven by various studies.

The positive point about this method is that it yields a quantitative and tangible analysis of the investigation which is minimally affected by environmental noises. Also, the test costs are low and the main cost is allocated to purchasing the camera. Moreover, it is possible to investigate larger structures with a camera and this removes the problems related to the size of the sample under investigation. However, the problem with the method is that due to slight differences in the length of the bolts in a structure, the detection of changes is difficult (Park, et al., 2015).

Radio Waves Processing Based Methods

These methods are based upon the fact that looseness of bolts usually involves some sort of rotating of bolts or nuts and monitoring this rotation can be used in detection of looseness. To this end, an RFID tag is placed on bolts and their placement is adjusted to zero degree of rotation. If the looseness process and consequently any spinning happens, the change is detected by a reader and displayed in interface software. Experiments have shown that the relationship between the reader and the tag for angles lower than 20 degrees yields best efficiency (Wu, et al., 2016).

Methods Based on Electromagnetic Fields

These methods are based on bolt rotation in the process of looseness. In this method, a cover containing a coil is placed on nuts or bolt heads. When the bolt starts to spin due to looseness, the magnetic field is changed and the looseness is detected. The theoretical basis for this method is simple, but the problem is that it can be used for one bolt only and this could cause problems for structures with a high number of bolts. Moreover, the looseness usually involves slight spinning and with such slight rotations, the changes in the magnetic field would be small, too, which results in a reduction in accuracy of the method (Park, et al., 2015; You, et al., 2010).

Methods Based on Electric Potential

When the process of looseness begins in a bolted structure, such as in two connected plates, the cross section area is increased and electric resistance is reduced. In such cases, if a specific electric current is applied to the structure, a voltage drop will happen, which can be used to detect the looseness. Although the method is theoretically simple, to use the method, all paints and covers must be removed from the structure and sensors must be placed around every bolt, and this leads to unfavorability of this method (Park, et al., 2015; You, et al., 2010).

Direct tension indicator method		
Type of Method: *Direct*	Nature of signal: *No Signal*	Suitability for online CM[1]: *NO*
Analysis field: *Without signal processing*		Relative cost of method: *Low*
Advantages: *Easy implementation, simple theory, low cost.*		
Disadvantages: *Low accuracy, not suitable for in situ monitoring, need for specific designs for each structure.*		
Strain gauges		
Type of Method: *Direct*	Nature of signal: *No Signal*	Suitability for online CM: *NO*
Analysis field: *Without signal processing*		Relative cost of method: *Low*
Advantages: *Easy implementation, simple theory, low cost.*		
Disadvantages: *Low accuracy, not suitable for in situ monitoring.*		
Torque control		
Type of Method: *Direct*	Nature of signal: *No Signal*	Suitability for online CM: *NO*
Analysis field: *Without signal processing*		Relative cost of method: *Low*
Advantages: *Easy implementation, simple theory, low cost.*		
Disadvantages: *more than 50% error, depending on inspector experiences, not suitable for in situ monitoring.*		
Impedance based methods		
Type of Method: *Indirect*	Nature of signal: *Impedance*	Suitability for online CM: *YES*
Analysis field: *Time or frequency.*		Relative cost of method: *Relatively high*
Advantages: *high sensitivity, suitable for in situ monitoring, acceptable performance for complex structures.*		
Disadvantages: *Relatively high cost, high size of setup, sensitivity to thermal and load fluctuations.*		
Case studies: *Bolted joints in pipelines* (Park, et al., 2003; Park, et al., 2001), *thin plates* (Pavelko, et al., 2011) *and experimental setups* (Ritdumrongkul, et al., 2004; Wait, et al., 2005; An & Sohn, 2012; Mascarenas, et al., 2009).		
Vibration based methods		
Type of Method: *Indirect*	Nature of signal: *Displacement, Velocity or Acceleration*	Suitability for online CM: *YES*
Analysis field: *Time, frequency or time-frequency.*		Relative cost of method: *Relatively low*
Advantages: *Theoretical and operational simplicity, relatively low cost, acceptable accuracy.*		
Disadvantages: *Depending on inspector experiences, barely suitable for in situ monitoring.*		
Case studies: *bolted joints in robots* (Trendafilova & Brussel, 2001; Tjahjowidodo, et al., 2007), *metal* (Guarino & Hamilton, 2009) *and composite* (Caccese, et al., 2004) *structures, pipelines* (Esmaeel, et al., 2012) *and experimental setups* (Adams & Farrar, 2002; Wit, et al., 1995; Nichols, 2007; Milanese, et al., 2008; Razi, et al., 2013).		
Piezo active sensing method		
Type of Method: *Indirect*	Type of Method: *Indirect*	Type of Method: *Indirect*
Analysis field: *Time or frequency.*		Analysis field: *Time or frequency.*
Advantages: *Relatively low cost, suitable for in situ monitoring, acceptable accuracy.*		
Disadvantages: *High size of setup for complex structures and consequently high costs.*		
Case studies: *Experimental setup* (Wang, et al., 2013; Chang & Yang, 2006; Doyle, et al., 2010).		
Acoustoelastic based methods		
Type of Method: *Indirect*	Nature of signal: *Time (TOF), Velocity (Velocity ratio) or Frequency (MRFS)*	Suitability for online CM: *NO*
Analysis field: *Time or frequency.*		Relative cost of method: *High*
Advantages: *simple and understandable theory, low sensitivity to environmental noises (TOF), No need to dismantle the bolts (Velocity ratio).*		
Disadvantages: *Inability to do online monitoring (TOF), need to dismantle the bolts (TOF), high sampling rate and consequently high costs.*		
Case studies: *bolted joints in steel structures* (Liew, et al., 2006) *and experimental setups* (Hirao, et al., 1994; Kawashima & Yasui, 2000).		
Side band method		
Type of Method: *Indirect*	Nature of signal: *Displacement, Velocity or Acceleration*	Suitability for online CM: *YES*
Analysis field: *Frequency or Time-Frequency*		Relative cost of method: *Relatively high*
Advantages: *High accuracy, suitable for in situ monitoring and low sensitivity to environmental noises.*		
Disadvantages: *Complicated theory, relatively high cost*		
Case studies: *Bolted joints in plates* (Meo & Amerini, 2011; Amerini, et al., 2010) *and experimental setups* (Meyer & Adams, 2015).		

Table 1: Summary of direct and indirect methods used in evaluation of bolted structures.

[1] Condition Monitoring

4 CONCLUSION

As was mentioned above, due to the fact that looseness begins with a decrease in the amount of axial force, the measurement and estimation of this force is among the most important strategies in monitoring bolted structures. To do this, there are various methods, the most useful of which are presented in Table 1. As was shown, direct measurement methods, while possessing simple theoretical basis and being easier to use, are employed less due to their low accuracy and significant error. In fact, because of this, the methods are less discussed in academic papers or for the investigation of important structures, though they are stated in standards. Among the methods presented in Table 1, those based on the acoustoelastic effect are hardly used for online monitoring of conditions. This is not the only problem of this group of methods, though, and the cost of the test is also significantly high, due to the high frequency sampling equipment. Even though the rest of the methods have the capacity to be used for online condition monitoring, the test expense is a noteworthy factor to be considered by the inspector. Lower costs would be incurred by the methods which are based on vibration and the piezo active sensing method. While both of these methods are based on monitoring variations of linear parameters, they have less accuracy, compared to non-linear methods. Due to this very reason, side bands methods which include the impact modulation and vibroacoustic modulation methods are regarded as the methods with the highest amount of sensitivity in detecting looseness in bolted structures, though the methods have theoretically complicated basis and would include relatively high expenses.

Thus, a number of different parameters should be taken into account when choosing the best method for detection and evaluation of looseness of bolted structures and consequently of axial force, the most salient of which are test accuracy, test cost and the feasibility of online monitoring. In fact, it is the circumstances under which the test must be performed and the required amount of accuracy that determine the importance of key parameters in choosing the most suitable method.

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