INTELLIGENT AUTOMATION & SOFT COMPUTING, 2017
http://dx.doi.org/10.1080/10798587.2016.1267245

Electro-Mechanical Impedance Based Position Identification of Bolt Loosening Using LibSVM

Yuxiang Zhang[a], Xin Zhang[a], Jiazhao Chen[b] and Jianhai Yang[a]

[a]602 office, Power Engineering Department, Xi'an Research Inst. of Hi-Tech, Xi'an, China; [b]601 office, Power Engineering Department, Xi'an Research Inst. of Hi-Tech, Xi'an, China

ABSTRACT
Bolt loosening is a common structural failure, which received extensive attention from many industrial departments. Because the uneven stress on different directions of a bolt is the common reason that the bolt becomes loose, it is quite important to carry out the research about sensitive detection of bolt loosening. Using Agilent 4924A instrument, this paper precedes the loosening test of bolts based on Electro-Mechanical Impedance (EMI), on an aluminum plate instead of flange plate for simplification. And the electromechanical admittance is given according to the fundamental equation of Piezo-Material Lead Zirconate Titanate (PZT). Specifically, the paper first studies the detecting sensitivity of EMI on bolt loosening; then, it shows that RMSD can be seen as a good damage index to identify damage; at last, our experiment result shows that by using LibSVM to process big data, the position of a loose bolt can be correctly identified from 12 possible bolt positions. The method mentioned in this paper shows the great potential to be used for the damage monitoring of bolted structure.

KEYWORDS
PZT; Admittance spectrum; Electro-mechanical impedance; LibSVM; Damage identification

1. Introduction

There are many different bolted structures in various systems from aerospace, aviation and navigation. The identification of a bolt loose problem has always been an important topic, because the bolted structure is used in many fields including military, transportation and construction, where a loose bolt may cause very severe troubles. Among many different approaches for bolted structure damage identifications, the EMI is selected for loose bolt identification in this paper for its high sensitivity in damage identification, wide linear range, being avoidable of far-field damage, and advantages of the PZTs pasted on the structure-light quality, high cost performance and being online (Zhang, Xu, Zhang, & Wu, 2012; Yaowen & Divsholi, 2010), compared to the traditional techniques like UT(Ultrasonic Testing), RT(Radiographic Testing), MT(Magnetic Testing), PT(Penetration Testing) and ET(Eddy current Testing), so it will have a broad prospect to apply EMI in damage identification of bolted structure.

There have been many research studies exploring using EMI for different diagnosis purposes. For example, Park S and Park G demonstrated an active health monitoring method, using a modified EMI model to implement the self-diagnosing of sensors (Park, Park, & Yun, 2010). Lorenzo Dozio studied the vibration of thin rectangular plates on arbitrary elastic boundary and their experiment had showed promising results (Dozio, 2010). In 2014, the team led by Professor Su Zhongqing in HKPU conducted an experiment using PZT to detect cracks caused by fatigue or stress in the bogie of a high-speed rail car. The study on detection of bolt loosening is lacking. In 2013, several researchers evaluated the firmness degree of bolts by damage index by using some PZTs and concluded that there is a linear relationship between damage index and torque with a certain range of 40~10 N•m (Liang & Youchen, 2013). This paper, however, proposes a quantitative bolt loosening identification method based on EMI, which using LibSVM to process a large number of experimental data can be used in various bolted structures of aerospace and aviation.

2. Structural Damage Identification Theory Based on EMI

EMI is a new structural health-monitoring technology, which is based on the whole vibration to detect structural local damage. Its theory (González, García, Benavente-Peces, & Pardo, 2016; Jicheng, 2012) is to contrast, analyze and synthesize the impedance/admittance (inverse of impedance) spectrum, which contains the information of structural condition, and then to extract the key information to detect and identify the damage in the structure effectively.

Admittance is the structural inherent attribute, which is a constant value for a certain structure. The admittance is also related to the structural condition, which makes it a good indicator for the structural damages. The admittance, which is defined in Equation 2, can be calculated by dividing the current of PZT using the voltage of PZT. To be more specific, the calculation of the admittance can be carried out through the following steps: ① Expanding the unidimensional fluctuant equation (Formula 1) of PZT to two-dimension to get the density of current, and ② integrating the current in the rectangle plane of thin plate.

$$\begin{aligned} \varepsilon &= \sigma / \overline{E_p} + d_{3i} E_3 \\ D_3 &= d_{3i}\sigma + \overline{\varepsilon_{33}}^T E_3 \end{aligned} \tag{1}$$

$$Y = j\omega \frac{b_p l_p}{h_p} \left(\overline{\varepsilon_{33}}^T - \frac{Z}{Z + Z_A} d_{3i}^2 \overline{E_p} \right) h_a \tag{2}$$

CONTACT Yuxiang Zhang yuxiangz@tom.com; Xin Zhang xinzhang@hit.edu.cn

Among formula 1, d_{3i} denotes electromechanical constant in the i direction under the zero electric field; ε and σ denote strain and stress respectively; D_3, E_3 denote the dignity of current and the strength of electric field respectively; and $\overline{E_p} = E_p(1 + j \times \eta)$, $\overline{\varepsilon_{33}}^T = \varepsilon_{33}^T(1 - j \times \delta)$ respectively denotes the plural Young modulus under the zero electric field and plural dielectric constant under the zero stress, where η, δ respectively means the mechanical loss factor and the dielectric loss factor. Among formula 2, Y, j and ω denotes the electromechanical admittance, imaginary number unit and angular frequency of stimulation imposed on the PZT respectively; l_p, b_p and h_p denotes the length, width and thickness of PZT respectively; and Z_A, Z respectively denotes electromechanical impedance of PZT and the main structure.

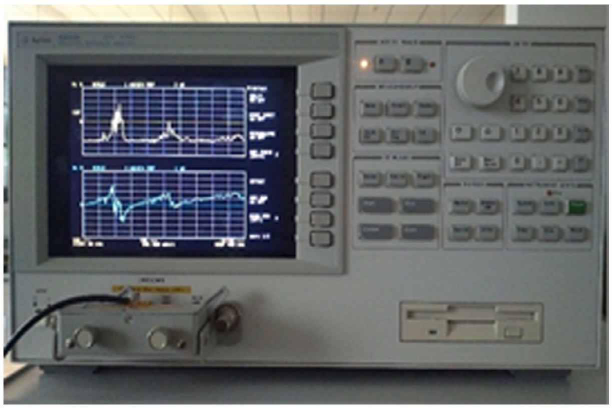


Figure 2. Impedance Analyzer Agilent 4924A.

3. Design of Systematical Scheme

3.1. The Experimental Principle

The experimental principle is described in Fig. 1, where the PZT is pasted on the aluminum plate and connected to the impedance analyzer Agilent 4924A (Fig. 2) to induce the change of structural condition. Electromechanical admittance before and after damage is measured by Agilent 4924A, and then the large amount of data transmitted to computer by Ethernet cable.

The high precise impedance analyzer Agilent 4924A is a kind of comprehensive test instrument, which can measure and analyze high-efficiently the impedance of component and circuit. With the automatic balancing bridge technology, its basic impedance accuracy can reach ±0.08% in the frequency range that the impedance analyzer covers. The impedance analyzer has excellent high Q/ low D accuracy that are suitable for analysis of low-loss component, and a wide range of signal level, which can make an accurate assessment of device under actual operating condition. In specific applications, different equivalent circuit model can be selected to comprehensively analyze the DUTs.

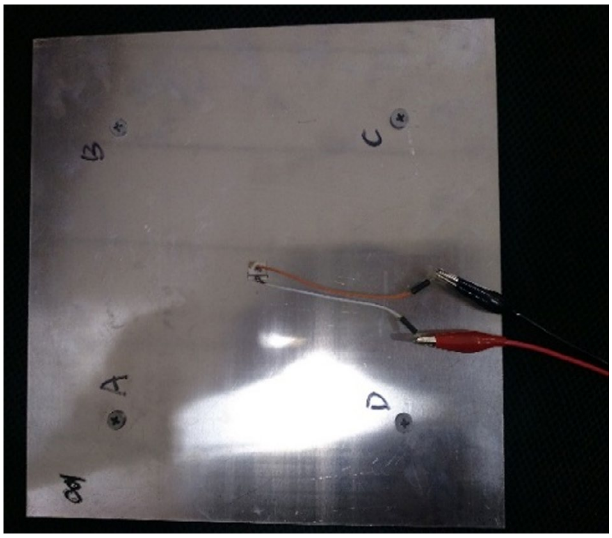


Figure 3. The Experimental Test-piece.

3.2. Design of Experimental Test-piece

The experiments are performed in the laboratory environment of 20 °C and humidity of 30%. The type of PZTs adopted is PZT-5A, which has the largest electromechanical coupling coefficient and can be used as driver and receiver. Using quadrate plate of l(length)× b(width)× h (thickness) = 250 mm × 250 mm × 3 mm as the research object, this paper studied the detection of bolt loosening in different positions. Four bolts named A, B, C and D are uniformly distributed on the plate, and the distance between the center of every bolt and the boundary of the quadrate plate is (40 mm, 40 mm). The size of PZT is 10 mm × 10 mm × 0.5 mm, which center is 75 mm far from line AB and 80 mm far from line BC, and its positive is toward line CD. The test-piece placed on the table in the way of simply supporting is shown in Fig. 3. The parameters of aluminum plate, PZT and stickup layer is respectively shown in Table 1–3.

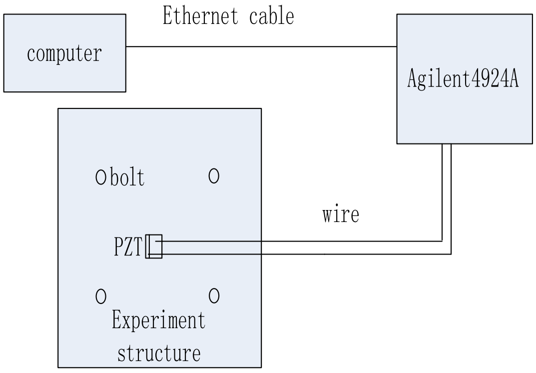


Figure 1. The Principle of Structure.

The high precise impedance analyzer Agilent 4924A is a kind of comprehensive test instrument, which can measure and analyze high-efficiently the impedance of component and circuit. With the automatic balancing bridge technology, its basic impedance accuracy can reach ±0.08% in the frequency range that the impedance analyzer covers. The impedance analyzer has excellent high Q/low D accuracy that is suitable for

Table 1. Parameters of Aluminum Plate.

Para.	E_r (Pa)	G_r (Pa)	μ	ρ_r (kg/ m^3)	η	l(mm)	b(mm)	h(mm)
Value	6.60E10	2.33E10	0.33	2700	0.01	250	250	3

Table 2. Parameters of PZT.

Para.	E_p (Pa)	ρ_p (kg/m^3)	$d_{31} = d_{32}$ (m/V)	$d_{15} = d_{24}$ (m/V)	d_{33} (m/V)	$\varepsilon_{11}=\varepsilon_{22}$ (F/m)	ε_{33} (F/m)	δ	η
Value	6.67E10	7800	−2.1E-10	5.8E-10	5E-10	1.7 E-8	2.14E-8	0.0185	0.03

Table 3. Parameters of Stickup Layer.

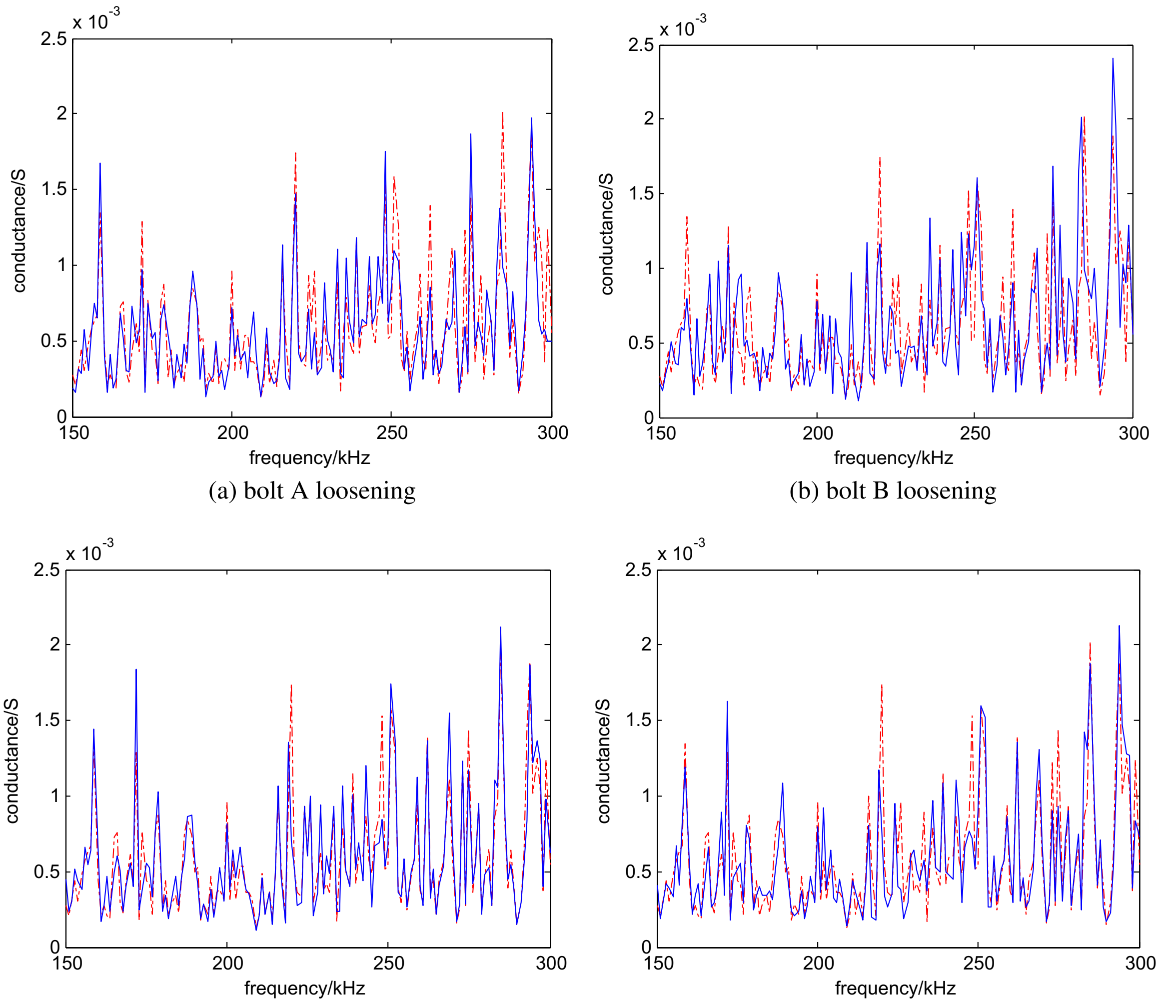
Para.	l_a(mm)	b_a(mm)	h_a(mm)	G_a(Pa)	ρ_a(kg/m^3)	C_a
Value	10	10	0.1	1.0E9	1700	100

analysis of low-loss component, and a wide range of signal level, which can make an accurate assessment of device under actual operating conditions. In specific applications, different equivalent circuit model can be selected to comprehensively analyze the DUTs. During the experiment, PZT is excited by the impedance analyzer in an alternating voltage of 1 V.

4. Analysis of Electromechanical Admittance Before and After Damage

Two groups of experiments are performed. Every bolt is measured four times at loose state for each group, in which the large-error measurement is filtered off and remaining three times is plotted as electromechanical admittance spectrum after averaging. Adopting control variable method, the first group looses one bolt each time and the loose quantity is 360°. The value of real part of admittance before and after bolt loosening is shown in Fig. 4. The second one denotes the state that one bolt is removed completely each time and the values of real part of admittance before and after that bolt is removed is shown in Fig. 5. The admittance spectrum has been measured six times and then is averaged to eliminate the accidental factors. The foregoing studies have shown that the real part of admittance can well reflect the structural damage and imaginary part is not sensitive to damage (Park, Sohn, Farrar, & Inman, 2003), so the abscissa is frequency domain for measurement and ordinate is conductance (the electromechanical real part of admittance), which unit is Siemen (Chen Yong, 2010). The sensitive frequency domain of thin plate-150~300 kHz, is obtained by simulation and experiment, which is closely related to the thickness and stiffness of experimental structure. The number of admittance measured by Agilent 4924A under different frequency is 300 each time, i.e., the step frequency is 50 Hz. Dotted line and solid line in the figures of real part of admittance respectively denote the state all bolts are tight and the damage state.

As can be seen from Fig. 4 and Fig. 5, the admittance spectrums of corresponding bolt after being loosed and removed (equivalent to hole damage) respectively is quite different, which suggests that the properties of bolt loosening and hole damage are variant; the admittance spectrums of the four bolts loosed successively are full of similarity in some frequency domain, and so are the admittance spectrums of the four bolts removed successively, which manifests that the admittance spectrums of one test-piece are similar at the same type of damage; the admittance deviation before and after damage is large, so the method is great to identify bolt loosening. Meanwhile, four kinds of information are gotten, and specific descriptions are as follows:



(a) bolt A loosening (b) bolt B loosening

(c) bolt C loosening (d) bolt D loosening

Figure 4. Real Part of Admittance Spectrum before and after that Bolt is Loosed.

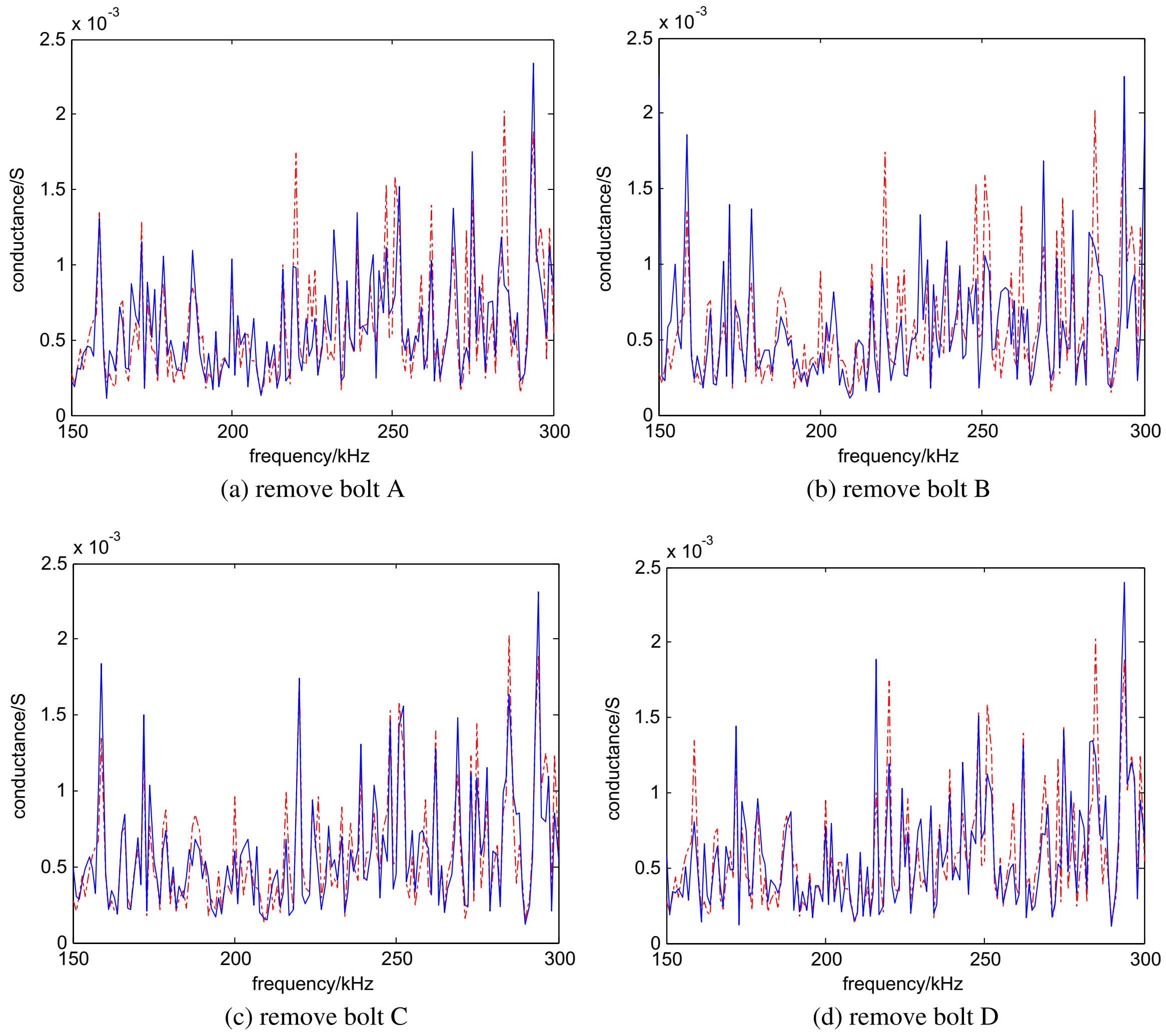


Figure 5. Real Part of Admittance Spectrum before and after that Bolt is removed.

- There are plenty of low peaks (< 3E-4 siemens), which are mainly due to the rough of four sides of plate caused in process. The admittance difference caused by these low peaks is quite small, which difference from the admittance difference caused by damage is very big on the orders of magnitude, so the admittance difference caused by these low peaks can be ignored.
- There are some slightly high peaks in the figures, which mainly are caused by asymmetry of PZT and called asymmetric modes.
- Some slightly high peaks appear bifurcate, divided into two parts, which is mainly, because there are not only flexural modes but also axial vibration modes.
- The peak of electromechanical admittance when a certain bolt is loose is lower compared with the state all bolts is tight, which is caused by the reduction of propagation energy after damage.

Statistical analysis on all data points has been conducted, and the measurement standard selected is root mean square deviation (RMSD) (Min, Park, & Yun, 2010; Seunghee Park, Kim, Lee, & Park, 2011), which is a great statistical value to reflect the degree of damage obviously. The corresponding calculation formula of RMSD is as follows:

$$RMSD = \sqrt{\sum_{N} \left[\mathrm{Re}\left(Y_i\right) - \mathrm{Re}\left(Y_i^0\right)\right]^2 / \sum_{N} \left[\mathrm{Re}\left(Y_i^0\right)\right]^2} \quad (3)$$

where, $\mathrm{Re}\left(Y_i\right)$ and $\mathrm{Re}\left(Y_i^0\right)$ denote respectively the real part of electromechanical admittance before and after damage in corresponding frequency, and N (= 300) stands for the number selected of frequency points in designate frequency domain. By calculation, visualized histogram of statistical quantity (Fig. 6) and damage index (Table 4) of electromechanical admittance before and after damage is obtained.

After removing the bolt, it can be obtained from the table that the damage index is bigger, compared with the state of bolt loosening. And there is a phenomenon-DI(B)> DI(A)> DI(C)> DI(D), which is mainly, because of the distance of bolts from PZT to result in the decrease of sensitive degree at different levels accordingly. That is to say, the closer the distance of bolt from PZT is, the bigger the damage index is, which can contribute to avoiding the influence of far field, as well as lays

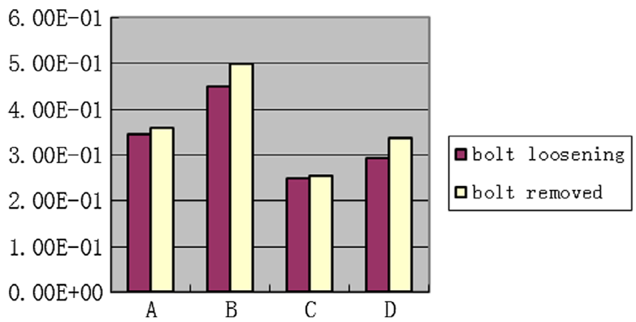


Figure 6. Statistical Quantity Histogram of Bolt Loosening.

Table 4. Damage Index, DI.

Bolt number	Distance from PZT	Bolt loosening	Bolt removed
A	117.15 mm	34.61534%	35.80257%
B	113.35 mm	44.97356%	49.98505%
C	124.20 mm	24.82940%	25.54925%
D	130.86 mm	29.33411%	33.78011%

a solid foundation for the subsequent accurately identifying damage position.

5. Application of LibSVM on Position Identification of Bolt Loosening Based on EMI

5.1. Introduction of LibSVM

LibSVM is simple easy to use and rapidly effective machine learning package used to pattern recognition and regression on the basis of SVM (Support Vector Machine). And it can solve problems like classification (including C-SVC and ν-SVC), regression (including ε-SVR and ν-SVR), and distribution (one-class SVM) (Tingyao, Peng, & Qin, 2015). It provides four frequently-used kernel functions to be selected, like linear function, polynomial function, radial basis function (abbreviation: RBF) and S form function, which can effectively solve the multiclass problem, cross validation to select parameters, weighting of imbalance samples and probability statistics of multiclass problem. Because of the characteristics of small procedures, use of flexible and less parameter, and the noticeable advantages that it is open, easy to extension, LibSVM now become widely used. In a practical application, the LibSVM is broadly applied to traffic prediction, wine quality evaluation; regional traffic volume forecast and grain moisture data fusion and so on. In the same way, in the field of nondestructive testing, LibSVM can also be used to conduct the classification and recognition of damage position.

5.2. Procedures of LibSVM

The specific steps of LibSVM are as follows:

- To prepare data-set in accordance with the format required;
- To narrow or amplify the data scale proportionally, because all the data processed in the normalized method is positive, the range after normalization is (0,1];
- To select RBF $K(x,y) = e^{-\gamma\|x-y\|^2}$;
- Using cross validation to select the best C (cost-penalty efficient, reaction to the tolerance of error, the value of it is often 1) and γ(= 1/k, the radius of kernel function, which determines the data distribution when it is mapped to the new feature space, and k denotes the number of attributes inputted), and choose 2 as the value of CV (Cross Validation) on the basis of experience;
- Adopting the best C and γ to train the whole trainingSet so as to obtain the SVM model;
- To test and forecast by use of the obtained model.

5.3. Experimental Design

Experimental specimen diagram is shown in Fig. 7. The length, width and thickness of experimental specimen are 400, 400 and 4 mm successively, and the length, width and thickness of piezoelectric patch are 20, 12 and 1 mm respectively. The diameter of all the 12 threaded holes is 6 mm, numbered 1#, 2# ... 12# respectively. The distance of the threaded hole 1# and three piezoelectric patches-PZT A, B and C from the boundary of plate is marked in the picture, and the unit of number is mm. The positive of piezoelectric patches is towards the right. The online damage detection based on PZT array is a problem of multi-source information fusion (Ren & Yang, 2013). Twelve bolt holes are evenly distributed, surrounding aluminum plate in the 90° symmetry, and the other parameters are same as above. In order to ensure learning efficiency, each bolt position is measured 50 times by each PZT, and each measurement is after the fact, that all bolts are tightened and that the corresponding bolt is loosen for a circle.

5.4. Data Collection

After the measurement, the original dataSet is divided into two parts using dichotomy. One is named the training set trainingSet that is used train the SVM model and another is the test set testingSet, which is used to check the model. Then treating the training set as test set and test set as the training set to iterate once again, the error obtained by two iteration will be processed as prediction error of the general data.

When using the LibSVM for training, the raw data-set consists of a 650 by 900 matrix, in which the row number is 650 (= 50+ 600= measuring times when all bolts are tight + the number of bolt × measuring times when a bolt is loose) on behalf of the number of samples, and accordingly the column number is 900 (= 300+ 300+ 300) on behalf of the number of attributes. For each row, the elements refer to the value of structural electromechanical admittance measured by PZT A, B and C every 0.5 kHz in the 150~300 kHz. The label is a column matrix containing 325 elements, and its content is made up with the number 0~12, in which 0 is on behalf of the state that all bolts is tight, namely there is no loose bolt and 1~12 denote respectively that the bolt of corresponding serial number is loosened for a circle. As a result, training samples and test samples are both 325 by 900 matrixes. In order to improve classification precision, training samples need to match with label after mapping, and then each parameter need to be tested by test samples to further examine the LibSVM model.

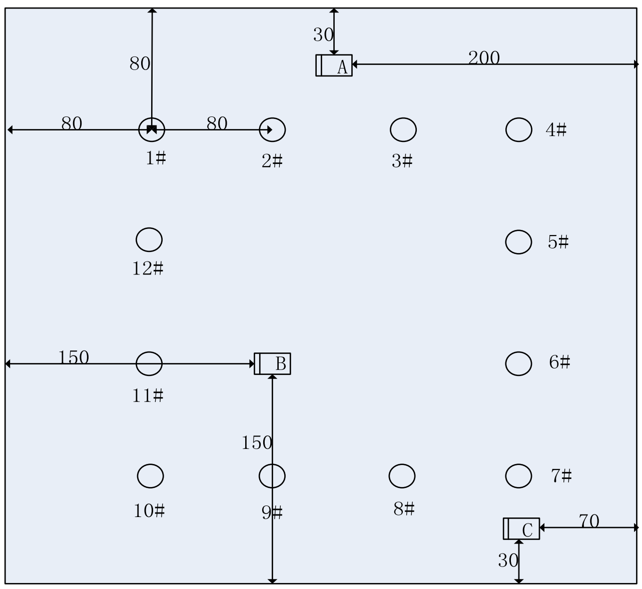


Figure 7. Structure Diagram of Plate with Bolts.

Table 5. Position Identification of Bolt Loosening.

Position	The largest probability	The second probability	Other	Result
1#	1 (64.7%)	2 (24.1%)	11.2%	1
2#	2 (76.4%)	1 (11.9%)	11.7%	2
3#	3 (60.1%)	2 (24.1%)	15.8%	3
4#	4 (64.7%)	5, 3 (20.1%)	5.1%	4
5#	5 (80.9%)	4 (10.4%)	8.7%	5
6#	6 (71.0%)	7 (15.2%)	13.8%	6
7#	7 (59.9%)	6 (14.4%)	29.7%	7
8#	8 (66.1%)	7 (15.6%)	2.7%	8
9#	9 (73.2%)	8 (12.5%)	14.3%	9
10#	10 (56.5%)	9 (24.1%)	19.4%	10
11#	11 (70.6%)	10 (22.1%)	7.3%	11
12#	12 (65.9%)	11 (18.1%)	16%	12

5.5. Results

After a large amount of data training above, the results of most samples can highly match with label except that some individual results slightly have large error. The following step is to measure a set of results to prove the feasibility of the LibSVM, that is to say, tighten all bolts firstly, then loose respectively one of 12 bolts once for a circle, and finally record the electromechanical admittance spectrum to identify the damage. The identification results are as follows:

The results mentioned above are consistent with the ground truth, namely, the experiment condition, which shows that this method can identify the position of bolt loosening with high accuracy. As can be seen from Table 5, none of the largest probabilities of different bolt positions is 100%, which is primarily because the number of training samples is not big enough. As the sample size increases, the identification result is expected to be more and more close to 100%. In addition, if the result is 100%, it indicates that this measuring sample is included in the training sample, which almost never exists in a practical nondestructive testing scenario.

6. Conclusions

In this paper, the EMI method is used to identify the loose position of different bolts in bolted structure. Through the above analysis, the following conclusions can be obtained: Firstly, the EMI method for detection of bolt loosening is effective, which can qualitatively and quantitatively identify damage position; next, the electromechanical admittance spectrum will reduce overall after bolt loosening, which is mainly caused by reduction of transmission energy due to the damage; then, the shape of the curve before and after damage is generally same, and only in the resonance points there appears some obvious difference; furthermore, the structural damage index will increase with the increase of damage degree, so it can be used as a quantitative criterion of damage; lastly, LibSVM can accurately identify the loose position of different bolts, which lays a solid foundation for on-line monitoring of complex structure with bolts.

It is stated that the above research is a preliminary study of electro-mechanical impedance method for bolt loosening. Currently, the vibration working condition, which can lead to bolt loosening to some extent, has not been considered. Moreover, the conclusions obtained from this research also need to be further verified by experiments. So, the future work is mainly to study the effect of environmental factors on the output admittance signal.

Disclosure statement

No potential conflict of interest was reported by the authors.

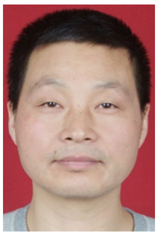
Funding

The authors would like to thank the National Natural Science Foundation of China (51275517 51105364) for financial support.

Notes on contributors

Yuxiang Zhang is a professor of Xi'an Research Inst. of Hi-Tech Hongqing Town, Xi'an, China. He received his Ph.D. degree in System Engineering from Xi'an Jiaotong University, Xi'an, China in 1998 and held Post-Doctoral Research from 1999 to 2003 in Xi'an Jiaotong University and Chinese Academy of Sciences respectively. His current research interests are in the areas of intelligent detection, fault diagnosis and information technology.

Xin Zhang is doctoral candidate of Xi'an Research Inst. of Hi-Tech Hongqing Town, Xi'an, China. He received a Master's degree in Vehicle Failure Physics and Reliability from Xi'an Research Inst. of Hi-Tech, Xi'an, China in 2015. His research interests focus on intelligent detection and pattern recognition.



Jiazhao Chen is a professor of Xi'an Research Inst. of Hi-Tech Hongqing Town, Xi'an, China. He received his Ph.D. degree in Mechatronic Engineering from Xi'an Research Inst. of Hi-Tech, Xi'an, China in 2007. His research interests cover design, condition monitoring and fault diagnosis of mechanical and electrical system.

Jianhai Yang is doctoral candidate of Xi'an Research Inst. of Hi-Tech Hongqing Town, Xi'an, China. He received a Master's degree in Vehicle Failure Physics and Reliability from Xi'an Research Inst. of Hi-Tech, Xi'an, China in 2009. His research interests focus on status monitoring and fault diagnosis.

References

Dozio, L. (2010). Free in-plane vibration analysis of rectangular plates with arbitrary elastic boundaries. *Mechanics Research Communications, 37*, 627–635. UK.

González, A.M., García, Á., Benavente-Peces, C., & Pardo, L. (2016). Revisiting the characterization of the losses in piezoelectric materials from impedance spectroscopy at resonance. *Materials, 9*, 72–89. Switzerland.

Jicheng, L. (2012). *EMI and its application research on damage detection of fatigue of aluminum alloy* (Academic Dissertation of Doctor's degree, Liaoning Province). Dalian University of Technology, China.

Liang, Ye, Youchen, Z., and Keqin, D. (2013). Mechanical bolt group looseness monitoring and recognition based on EMI. *Science Technology and Engineering, 13*, 5172–5176. China.

Min, J., Park, S., Yun, C.-B. (2010). Impedance-based structural health monitoring using neural networks for autonomous frequency range selection. *Smart Materials and Structures, 19*, 125011–125020. UK.

Park, G., Sohn, H., Farrar, C.R., Inman, D.J. (2003). Overview of piezoelectric impedance-based health monitoring and path forward. *The Shock and Vibration Digest, 35*, 451–463. USA.

Park, S., Park, G., Yun, C.B., and Farrar, C.R. (2010). Sensor self-diagnosis using a modified Impedance model for active sensing-based structural health monitoring. *Structural Health Monitoring, 8*, 71–82. USA.

Park, S., Kim, J.-W., Lee, C., Park, S.-K. (2011). Impedance-based wireless debonding condition monitoring of CFRP laminated concrete structures. *NDT&E International, 44*, 232–238. USA.

Ren, D., & Yang, S.X. (2013). Intelligent pattern recognition technology and applications. *Intelligent Automation & Soft Computing, 19*, 497–499. Switzerland.

Tingyao, J., Peng, L., & Qin, Q. (2015). An application of SVM-based classification in landslide stability. *Intelligent Automation & Soft Computing, 22*, 267–271. USA.

Yaowen, Y., & Divsholi, B.S. (2010). Sub-frequency interval approach in electromechanical impedance technique for concrete structure health monitoring. *Sensors, 10*, 11644–11661. Switzerland.

Yong, C. (2010). *Research on piezoelectric impedance of technology for structural health monitoring* (Academic Dissertation of Master's degree). Zhejiang University, Zhejiang, China.

Zhang, Y., Xu, F., Zhang, T., Wu, C. (2012). Application of electro-mechanical impedance sensing technique for online aging monitoring of rubber. *Intelligent Automation & Soft Computing, 18*, 1101–1109. USA.