Damage Identification of Semi-Rigid Connection in Structures Based on Nonlinear Vibration Characteristics

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Abstract. A damage-detection methodology based on nonlinear vibration characteristics was presented in this paper to identify damage of semi-rigid connections due to looseness of high strength bolts. In various damage cases caused by different loose severity of bolts in different positions, a specimen with semi-rigid connections was tested and acceleration signals of free vibration were recorded by sensors placed at its both ends. The recorded signals were then dealt with by wavelet de-noising and blind source separation to get the first vibrational components. By Hilbert transform of these components, the amplitude-frequency curve of each case was obtained. The results showed that vibration of the specimen with semi-rigid connections presented typical nonlinear characteristics. With the increase of connection damage, the nonlinear degree increased accordingly. When one end had larger connection damage than the other one, it exhibited greater nonlinear extent. The results prove that it is valuable to apply the suggested nonlinear vibration characteristics based procedure to identification of semi-rigid connection damage.

1. Introduction
A steel structure has superiority over a reinforced concrete structure, such as high strength, good seismic performance and fast construction speed and so on. As the price of steel continues to fall and structures are developing towards super height and large span in China, steel structures are applied more and more widely in civil engineering. In either a steel structure or a steel-concrete composite structure, semi-rigid connections made with high strength bolts are often used. Under the effect of service load and environmental factors for a long time, bolts in a semi-rigid connection are prone to looseness or even falling off, which will reduce the structural stiffness, change the mechanical model and constitute a potential safety hazard. Without being detected in time, this small damage may even lead to serious safety accidents.

Traditional ways to check looseness of bolts are torque method and rotation method. For a large-scale structure having a lot of high strength bolts, the two methods are highly time and labor consuming. There have been a few research reports on using damage identification techniques to detect bolt looseness. Diagnosis of bolts looseness and falling off in electrical transmission towers due to environmental effect was studied by Qu et al. [1], in which the variation of strain curve at joints of a tower was used. In another technique, PZT sensors were put at joints and looseness of bolts was detected by the change of electric admittance (Wang et al. [2]). The theoretical analysis and test results showed that the electric admittance given by sensors on the connecting plate of joints are sensitive to looseness of bolts. Haynes and Yeager [3] used ultrasonic technology to detect bolt...
looseness. Sensors were mounted on the surface of a bolted steel sheet to receive the ultrasonic signal. The severity of bolt looseness was recognized by the transmission of ultrasonic energy. Taheri and Esmaeel [4] identified bolt looseness by the energy damage index, which was constructed by the intrinsic mode functions (IMF). Piezoelectric sensors were used to collect the vibration signals of a laboratory-scale single lap joint. The acquired signals were then processed using empirical mode decomposition and the energies of the obtained IMFs were calculated to identify bolt looseness.

In vibration environment, tangential friction slip and normal gap impact may occur on any interface, which is called interface effect. The interface effect can lead to the change of stiffness and energy dissipation at the contact interface, further give rise to the change of the frequency and damping of the related structure. So the structural dynamic response exhibits typical nonlinear vibration characteristics [5-8]. Since the end of last century, some scholars have successfully used the nonlinear vibration characteristics to identify the damage of the reinforced concrete beam and pre-stressed beam [9-12]. For a concrete beam with cracks, the interface effect may occur at the crack interface during vibration. Consequently the vibration process of the concrete beam will exhibit nonlinear vibration characteristics. The same goes for a semi-rigid connection with high strength bolts of a structure. There exists interface effect on the interface of two steel plates of the semi-rigid connection. The variation of the connecting stiffness due to bolt looseness will change the interface effect and accordingly cause clear change of nonlinear vibration characteristics of the structure. Hartwigsen [13] found that nonlinear vibration characteristics existed in structures connected by bolts. In Heller’s study [7], two steel plates with different thickness were bolted together to form a composite beam and hung with steel wires. Under different pre-stress of the bolts, the damping and frequencies of the composite beam were analyzed. It was found that with the reduction of pre-stress of the bolts, the nonlinear vibration degree increased. In this paper, nonlinear vibration characteristics will be used to identify damage of semi-rigid connection resulted from bolt looseness.

Structural damage identification using nonlinear vibration characteristics has the following advantages. Firstly, the damage can be judged directly according to the nonlinear vibration characteristics of the structure, i.e. any structural reference state is unnecessary. Secondly, the method is robust to noise and less affected by temperature, boundary conditions and other factors. In addition, it is simple and quick, easy to run. Only common dynamic test equipment and a small number of sensors are required to complete the test. Therefore, this method has great potential in engineering application.

2. Test Procedure
A steel beam was connected to two steel columns at both ends. Frictional high-strength bolts were used to make semi-rigid connections. To form various damage cases, the bolts were applied different torques. In each damage case, vibrational tests with impact excitation were conducted on the beam and acceleration signals of free vibration were recorded by sensors placed at both ends of the beam. The acceleration signals were dealt with by wavelet de-noising and Blind Source Separation to get the first order vibrational components of various damage cases. By Hilbert transform of these components, the amplitude-frequency curve of each case was obtained. In the end, the relationship between the nonlinear vibration characteristics and the damage degree of semi-rigid connection would be proved. The flow chart of damage identification scheme is shown in figure 1.
2.1. Specimen and Test Setup

**Specimen:** The test object was a steel I-beam (Q235) with length of 5 meters, both ends of which were connected to end plates and fixed on two H-type steel columns respectively by six frictional high-strength bolts (M20) in the Structural Laboratory of Chongqing University.

**Test Setup:**

- Bolt loosening equipment: torque wrench with the torque range of 0-500 N·m, the torque could be controlled arbitrarily.
- Exciting equipment: a rubber hammer with weight of 0.8 kg.
- Signal acquisition equipment: DH5935N dynamic signal test and analysis system, DH105 piezoelectric accelerometer sensors.

The specimen and the sensors arrangement are shown in figure 2.

![Figure 2. The specimen: (a) Side view. (b) N-N section view.](image)

2.2. Vibrational Tests

According to the code for design, construction and acceptance of steel structure high-strength bolts connection, the turning tight torque $T_c$ of frictional high-strength bolt was 408 N·m. The value was set to 400 N·m for convenience. During each test, once the torque value of high-strength bolt reached 400 N·m, it was considered that the connection between the steel beam and column was not damaged.

In the experiment, three cases of damage states were designed: case 1, keeping the bolt torque 400N·m unchanged for all bolts of end A, bolt torque of all bolts at end B was reduced gradually from 400N·m to 50 N·m by the step size 50 N·m; case 2, the bolt torques at both ends changed simultaneously from 400N·m to 50N·m by the step size 50 N·m; case 3, the bolt torques changed by different value at both ends. Detailed damage states are shown in table 1. It should be pointed out that, if all of the bolts at one end are completely loose, i.e. the torque is 0 N·m, the damage is so obvious to be found that any detection technique is unnecessary. So no damage case was considered for such situation.
Table 1. Damage states.

| Case 1       | Case 2       | Case 3       |
|--------------|--------------|--------------|
| A400B400     | A400B400     | A200B400     |
| A400B350     | A350B350     | A150B300     |
| A400B300     | A300B300     | A100B200     |
| A400B250     | A250B250     | A50B100      |
| A400B200     | A200B200     |              |
| A400B150     | A150B150     |              |
| A400B100     | A100B100     |              |
| A400B50      | A50B50       |              |

A400B200: The A end torque is 400N·m and the B end torque is 200 N·m, others have similar meanings.

For each damage case, three dynamic tests were carried out. The steel beam was excited by hammer impact at the middle span. Then the acceleration signals of free vibration were recorded by the sensors mounted near the both ends with the sampling frequency being 1024 Hz. The excitation force was not too large and roughly kept the same as far as possible.

3. Results and Analysis

Take the case of A400B200 for example, a frequency spectrum analysis of the free vibrational signal collected by the third sensor was made. It was found that there were some small peaks in addition to a number of large peaks in the power spectrum. This indicated that the signal involved more than one order vibrational component meanwhile contained measuring noise.

3.1. Signal De-Noising

In order to deal with measuring noise, a technology called wavelet soft threshold de-noising was applied [14]. The choice of the threshold parameter L was a tradeoff, which means removing noise as much as possible and avoiding excessive distortion of the signal. Repeated trials showed that the value of 4 for L was the best. Figure 3 shows a de-noised free vibrational acceleration signal of A400B200 and its power spectrum. Comparing the power spectrum with that of the signal before de-noising, it was found that small peaks disappeared.

![Figure 3. The acceleration signal of A400B200 after de-noising (a) and its power spectrum (b).](image-url)

3.2. Blind Source Separation

The signals of A400B200 recorded by the third and fourth sensors were de-noised respectively and then used to get the first order vibrational component by the SOBI algorithm [15]. The obtained first order vibrational component and its power spectrum are shown in figure 4.
3.3. Time-Frequency Relationship

Since the signal recorded by the sensor was acceleration, it needs to be converted to displacement before going to the next step. The first order vibrational component obtained by the procedure described above was integrated twice to get the displacement signal, which was then transformed by Hilbert transform to obtain the time-amplitude and time-frequency curves. The endpoint effect was dealt with by the mirror method [11-12]. The amplitude-frequency curve could be drawn by combining the time-amplitude and the time-frequency curves. A typical amplitude-frequency curve of end B under A400B200 is shown in figure 5.

![Figure 5](image-url)
Following the above procedure, the amplitude-frequency curves of end A and end B could be obtained under various damage states. For convenience of comparison, the curves were normalized when they were drawn together, i.e. the ordinates of each curve were subtracted by its maximum value of frequency. So the nonlinear vibration characteristics of the semi-rigid connection under various damage states are easy to be seen from the normalized curves as shown in figure 6.

![Normalized amplitude-frequency curves](image)

**Figure 6.** The normalized amplitude-frequency curves: (a) Curves of case 1 at end B; (b) Curves of case 2 at end A; (c) Curves of case 3 at end A; (d) Curves of case 3 at end B.

In general, all curves in figure 6 present nonlinear characteristics, i.e. the frequency decrease with the reduction of amplitude, with different degrees. For case 1 shown in figure 6 (a), with the increase of semi-rigid connection damage, i.e. the bolt preload of end B being decreased, the nonlinear extent at end B is increasing. That is, within the same variation of the vibratory amplitude, the frequency change is growing. The same analysis was carried out for that of end A. However, the amplitude-frequency curves were too close to each other to be distinguished. The largest frequency change didn’t exceed 0.04 Hz, which indicated very weak nonlinearity. The curves of end A were omitted due to space limitations.

The analysis results of case 2 are shown in figure 6 (b), with the increase of connection damage at both end A and B, the nonlinear degree increases at end A. Comparing with the curves in figure 6 (a), the nonlinear degree of case 2 is greater than that of case 1. This is attributed to connection damage at both ends of case 2. The amplitude-frequency curves of end B were almost the same as that of end A, so they were not drawn.
The analysis results of case 3 are shown in figure 6 (c) and 6 (d). The situation is similar to case 1 and case 2. The nonlinear extent of both end A and end B becomes significant with the increase of connection damage. For convenience of quantitative comparison, the frequency changes of end A and end B under each damage state within the amplitude range $2.5 \times 10^{-6} - 2.25 \times 10^{-5}$ m were calculated. The results are listed in Table 2. Under the same damage state, the nonlinear degree of end A was larger than that of end B. This is in agreement with the larger connection damage at end A comparing with that of end B.

**Table 2.** The frequency change values of end A and end B of each damage state/Hz.

| Damage state | A50B100 | A100B200 | A150B300 | A200B400 |
|--------------|---------|----------|----------|----------|
| End A        | 0.5321  | 0.3386   | 0.1617   | 0.1126   |
| End B        | 0.3955  | 0.2249   | 0.1224   | 0.0285   |

4. Effect of Number of Loose Bolts

In practice, for a specific semi-rigid connection, the position and number of loose bolts are often uncertain. It is necessary to take into account the effect of the number of loose bolts on the nonlinear vibration characteristics. Three typical damage cases were constructed as shown in figure 7, i.e. case 4, the corner bolt being loose; case 5, bolts at the diagonal positions being loose; case 6, bolts of the top row and the bottom row being loose. For each case, only three damage states were considered. They were A400B400, A400B200, and A400B0 respectively.

![Figure 7. Three damage cases considering different positions and number of loose bolts: (a) Case 4: corner; (b) Case 5: diagonal; (c) Case 6: top and bottom row.](image)

By the same steps described as above, the amplitude-frequency curves were obtained and shown in figure 8. It can be seen in figure 8 (a) that for A400B200 the frequency change is only 0.035 Hz when the amplitude decayed from $2.5 \times 10^{-5}$ m to $1.0 \times 10^{-5}$ m. That means the nonlinear vibration characteristics is not obvious, which is very close to the intact state A400B400. When the corner bolt is completely loose, i.e. A400B0, the frequency change is increased to 0.055 Hz. For case 5, as shown in figure 8 (b), the frequency change is 0.045 Hz for state A400B200 and increased to 0.073 Hz for state A400B0. As shown in figure 8 (c), case 6 has almost the same frequency change as case 5 for state A400B200 and experiences a larger frequency change than case 5 for state A400B0, i.e. 0.10 Hz.
Figure 8. The normalized amplitude-frequency curves: (a) Curves of case 4; (b) Curves of case 5; (c) Curves of case 6.

It can be concluded that the increase of loose bolt number will add to the nonlinear degree. So does the preload decrease of bolts. When there was only one loose bolt, e.g. case 4, the change of nonlinear characteristics was unapparent when the preload reduced by a half. However it could still be distinguished from the intact state without much confidence. When the only one loose bolt was totally deprived with preload, the nonlinear degree became big enough to make obvious difference with the intact state. When there were two loose bolts, i.e. case 5, the difference of nonlinear characteristics became easier to be identified by means of amplitude-frequency curves in figure 8 (b). After the number of loose bolts increased to 4, i.e. case 6, the situation was similar to that of case 5. However, the nonlinear extent became much bigger than that of case 5 when all the loose bolts lost preload.

5. Conclusions
Damage of semi-rigid connection caused by loosing of high strength bolts is common in practice. A nonlinear vibration characteristics based procedure was put forward to identify such damage. Through experiments and analyses, the suggested procedure was tested and conclusions can be drawn as follows:

(1) The first order vibrational component of a recorded acceleration signal could be successfully extracted by blind source separation SOBI algorithm, with the help of wavelet de-nosing technology to reduce measuring noise. With the first order vibrational component, it is easy to obtain the amplitude-frequency curve through Hilbert transform.

(2) Nonlinear vibration characteristics, i.e. the frequency rises with the amplitude reduction, exhibited by amplitude-frequency curves, exist in the free vibration of structural members connected by semi-rigid connections. Bolt loosing of a semi-rigid connection can be reflected by the change of nonlinear vibration characteristics. In general, with decrease of bolt preload and/or increase of the number of loose bolts, the nonlinear degree increases.
(3) For a beam with two semi-rigid connections, the free vibration of the beam adjacent one semi-rigid connection having loose bolts exhibits larger nonlinear degree than that nearby the other one. If both connections have loose bolts, the free vibration of the beam next to the connection with more loose bolts or/and severer loosing experiences larger nonlinear extent.

(4) When the bolt loosing is slight, i.e. the preload reduction of bolt is little and the number of loose bolts is small, the nonlinear characteristics difference is not obvious between the damage and intact state.

It is worthy to carry out further study to improve the suggested procedure dealing with bolt loosing of slight degree against measuring noise. Nonlinear vibration characteristics method is a valuable indicator to identify bolt loosing of semi-rigid connection.

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