Hindawi
Shock and Vibration
Volume 2019, Article ID 2036509, 8 pages
https://doi.org/10.1155/2019/2036509

Research Article

Experimental Study and Life Prediction of Bolt Loosening Life under Variable Amplitude Vibration

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Received 23 July 2019; Accepted 3 October 2019; Published 5 November 2019

Academic Editor: Sundararajan Natarajan

The transverse vibration test of bolts has been designed with adoption of the fatigue tester to study the features of the loosening life of bolts. Firstly, the transverse vibration frequency has been changed, the effects of the amplitudes of displacement, velocity, and acceleration on the loosening life of bolts have been compared, and it has been confirmed that the transverse displacement amplitude is the main factor that affects bolt loosening in low-frequency vibration. Secondly, the loosening degree of the bolts preloaded standard under five displacement amplitude grades has been monitored and the bolt loosening situation has been expressed through the residual preload-vibration times curve. The data of each stage of residual preload under each displacement amplitude were summarized, and the displacement-life (*D-N*) curve of bolt loosening under different loosening situations (percentage of residual preload) which is referred to the material fatigue life *S-N* curve was drawn. Finally, the accumulation mechanism of bolt loosening has been studied and the linear accumulation model of bolt loosening has been set up through designing variable amplitude vibration tests at high-low and low-high displacement stages. Results show that, through the bolt loosening *D-N* curve, it can be found out that the bolt loosening life curve and the material fatigue life curve are with features of double line and high- and low-cycle boundary under the logarithmic coordinate. Linear accumulation of bolt loosening is with similar principle of linear damage accumulation of material fatigue. Therefore, the bolt loosening life can be predicted through bolt displacement-loosening life (*D-N*) curve attained from the experiment and the established linear accumulation model of bolt loosening.

1. Introduction

In engineering application, it is very common for bolts to loosen when vibrating. The fatigue failure caused by the inadequate bolt tension is the main form of bolt vibration failure. In 1940s, the research on the self-loosening phenomenon of high-strength bolts has already begun, but there are still a lot of problems unsolved at present. The vibration forms at each bolt connection on mechanical devices are different. Bolt connections under different amplitude conditions have different loosening processes. The bolt loosening life can be predicted effectively if a rule of bolt loosening life is found by using the method for studying fatigue properties of materials (such as *S-N* curve). It is of great guidance significance for the design and practical production and maintenance of bolt connection.

In 1969, Junker published the most important paper on the loosening of threaded fasteners to date [1]. In the paper, Junker described the experiment with the new equipment (it is called as "Junker vibration tester"). Through this experiment, Junker obtained the relationship among relative displacement between the clamped pieces, transverse (vertical to the bolt axis) force, and the axial residual preload applied to the bolt. He proposed that the influence of the transverse (vertical to the bolt axis) load or displacement on bolt loosening is the biggest.

The Junker loosening model is shown in Figure 1. Solid A is placed on plane B which has a certain slope. If the inclined angle of plane B is smaller than its friction angle, solid A will not slide downward. When reciprocating transverse vibration $\pm S$ happens to plane B and makes the resultant force of the inertial force and the component of gravity force along

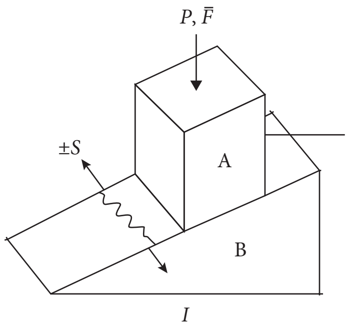

Figure 1: Junker loosening model.

the cant of solid A exceed the maximum static friction, solid A will have a downward velocity component along cant. Analogy to the threaded connection, the relative motion along the loosening direction has been produced between bolt and other components.

Studies made by Jiang and his colleagues showed that bolt loosening can be divided into two stages [2–8]. The first stage is the material loosening stage. Plastic deformation of the material causes decrease of the bolt tension. During this stage, the relative motion between the bolt and the nut is very small. The second stage is the structure loosening stage. The relative rotation between the bolt and the nut causes an obvious decrease of the tension.

For the material loosening stage: Jiang confirmed that the loosening of the bolts subjected to cyclic transverse loads in the material loosening stage was caused by cyclic plastic deformation of the screw thread by experimental observation and the elastoplastic finite element model [7]. Under the effect of the cyclic load, the plastic zone at the fillet of the screw thread will gradually expand due to the existence of the ratcheting effect.

For the structure loosening stage: by analyzing the results of the finite element analysis, Pai and Hess of the University of South Florida argued that the contact states could be divided into two categories: partially sliding and fully sliding [9]. The transverse load required for partially sliding is much smaller than that required for fully sliding.

Nassar and Housari [10–15] proposed a mathematical model based on the differential equation and experiment to study the bolt loosening caused by vibration. They also studied the influence of the pitch, preload, hole clearance, friction, and transverse excitation on loosening. The research indicates that, for the same load amplitude, the load frequency does not have much influence on the force conditions of bolts. But because the sliding time of each cycle at low frequency is longer, the bolt tension drops more under the same cycle times, so the lower frequency may makes the bolt easier to loosen.

After Housari, Nassar and Yang [16–20] established a more accurate mathematical model based on the relative sliding of the friction surface to solve the tangential force and the friction torque at the support surface and the thread under the cyclic transverse load. They came up with a loosening analytical criterion in this form of the fastener.

Hou [21] summarized in his paper that, for the material loosening stage, the greater the amplitude of vibration displacement, the greater the material plastic deformation degree and speed, which will cause the degree and speed of tension reduction increasing; for the structure loosening stage, it can be learned from the Junker loosening model in Figure 1 that the greater the transverse motion amplitude $\pm S$, the easier it is to move the solid A relative to the slope. It indicates that it is easier for the bolt and the nut to produce relative motion and the bolt loosens faster in this case.

Li and others from Tsinghua University conducted experimental research on the bolt loosening process under transverse vibration [22]. They found through the numerical fitting for the clamping force attenuation curve that, at preliminary loosening stage, a double exponential function relationship is satisfied between the clamping force and the transverse vibration times. The amplitude of the displacement vibration affects three parameters of the model function directly. The geometric research and the mathematical model derivation prove that the bigger the vibration displacement amplitude, the easier the bolt loosening.

Jing from Southwest Jiao Tong University did the research on the loosening behavior of three threaded connection structures under shear excitation [23]. He developed a loosening test device for the threaded connection structures under shear excitation and a test device for measuring the rotation angle of the nut. And he reproduced the loosening process of the threaded connection structure under shear excitation through experiments.

In recent years, Wang et al. conducted a comparative test on bolts with nonmetallic gaskets of different hardness between bolts without gaskets. It was found that bolts with nonmetallic gaskets of higher hardness have better effect on preserving the preload [24]. Fort presented a new analytical model with an improved criterion that could be used to predict the self-loosening of bolted joints [25]. Yamagishi et al. clarified the mechanical behavior of bolted joints under transverse loads and presented the critical relative slippage [26].

In summary, the existing research has elaborated on the mechanism of bolt loosening from theory and experiment. Although some details have not been studied clearly, the overall theory has matured. In actual production, the requirements for the bolt loosening life are very high, and the existing research does not elaborate on the loosening life. In this paper, with reference to the actual situation, the experimental study on the loosening life of bolts under variable amplitude vibration conditions was carried out.

2. Overall Test Route

Two steel plates were connected by M10 bolts. According to the standard, the preload of the M10 high-strength bolt should be controlled at around 26 kN. The initial preload was adjusted to standard by the pressure sensor on the bolt (all tests below maintain a uniform standard preload). Tightened specimens were installed on the electrohydraulic servo fatigue tester. The study on the impact of the amplitude change of displacement, velocity, and acceleration on the relationship between residual preload of bolt and time of loosening cycles was conducted by referring to the material fatigue test method to establish a research method for predicting the bolt loosening life.

In the experiment, *Shimadzu* electrohydraulic servo fatigue tester was used to load transverse vibration on the bolt connection. The tester and the computer equipment are shown in Figure 2. The tester specifications are shown in Table 1.

The vibration module of the tester is composed of two parts: upper and lower parts. The lower part is fixed on the base and the upper part is the hydraulic vibration part. The two parts are connected to the steel plate and are centered by the centering groove on the device to ensure that the bolt will not be affected by the external bending load caused by the eccentric clamping. The bolts tighten the steel plate tightly with the standard preload. The upper steel plate can vibrate by a certain frequency and amplitude through the tester. The pressure sensor locates between the bolt head and the steel plate to monitor bolt clamping force in real time. The test device sketch is shown in Figure 3. The fixtures are shown in Figure 4. The actual device installation is shown in Figure 5. The annular pressure sensor parameters are shown in Table 2.

3. Research on Influencing Factors of Loosening

The sinusoidal excitation used in this test was as follows:

$$d(t) = d_{\max} \sin(2\pi f t), \quad (1)$$

where $d_{\max}$ is the displacement amplitude (mm) and f is the vibration frequency (Hz).

The displacement amplitude $d_{\max}$ was kept constant. The maximum velocity excitation $2\pi f d_{\max}$ and maximum acceleration excitation $-(2\pi f)^2 d_{\max}$ would be changed through changing the frequency f. The time life was changed into life of the cyclic time. And the factors affecting the bolt loosening life could be found by comparing loosening cyclic times under different frequencies f and different maximum displacement excitations $d_{\max}$.

The bolt vibration test is mostly done under the low-frequency vibration. The recommended vibration frequency is 12 Hz in the bolt transverse test standard. Regardless of the high-frequency vibration, the low-frequency vibration was adopted in the test in this paper. Main factors affecting loosening were determined by two groups of controlled trials. One group compared the frequency 5 Hz with 10 Hz under the premise of displacement amplitude of 0.6 mm. The other group compared the displacement amplitude 0.4 mm with 0.6 mm under the premise of frequency of 5 Hz.

The results of the two groups of controlled trials are shown in Figure 6.

In Figure 6, the green line and the red line indicate the vibration times of the tests in 5 Hz and 10 Hz, respectively and the black line indicates the 70% residual preload. The green line and the red line intersect the black line at about 3200 vibration times. Thus, the tension in each test has decreased by 30% at around 3200 vibration times, which indicates that there is small relevance between the bolt loosening and the vibration frequency. With the increasing of the displacement amplitude, the tension decreases significantly. In the experiment with vibration amplitude at 0.4 mm drawn as the blue line, it needs around 9000 times for tension to decrease by 30%.

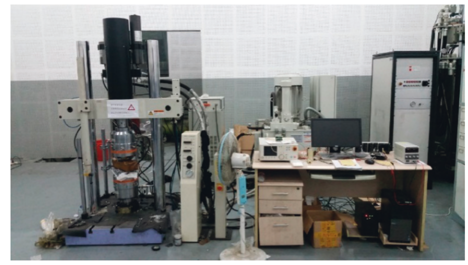

Figure 2: Electrohydraulic servo fatigue tester.

Table 1: Tester specifications.

Item	Parameter
Load capacity (kN)	±50 kN, ±100 kN, ±200 kN
Piston stroke (mm)	±25/50 mm
Load accuracy	±0.5% of the displayed value

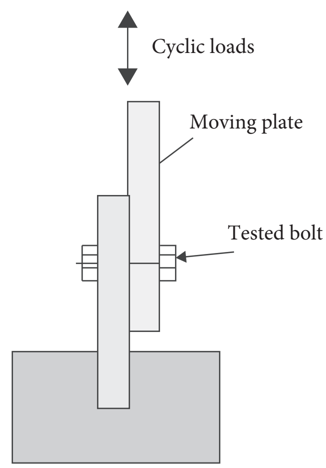

Figure 3: Test device sketch.

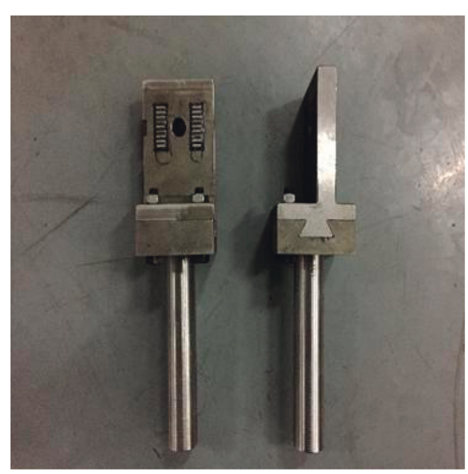

Figure 4: Testing fixture.

In summary, in the low-frequency vibration below 20 Hz, the main physical quantity that controls the bolt loosening is the vibration displacement amplitude, rather

Figure 5: Test device installation.

Table 2: Annular pressure sensor parameters.

Item	Parameters
Model	EVT-14T3-10T
Range (T)	10
Sensitivity (mV/V)	1.6229

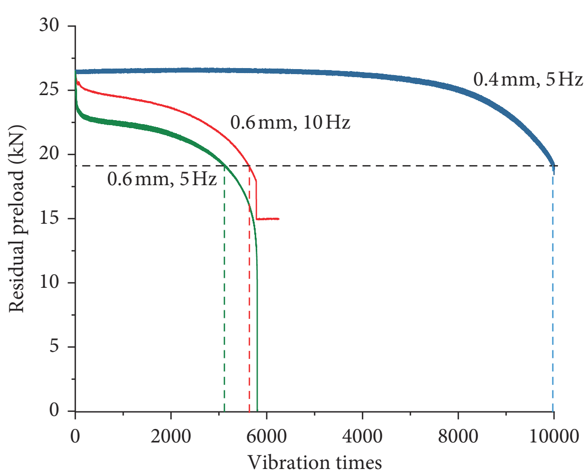

Figure 6: Loosening curves of two groups of contrast experiment.

than the velocity amplitude or acceleration amplitude, which verifies the conclusion of Junker.

4. Displacement Amplitude Grade Tests

In order to study the effect of different displacement amplitude grades on bolt loosening, five displacement amplitude grades of 1 mm, 0.8 mm, 0.6 mm, 0.4 mm, and 0.3 mm were set. Each test with different displacement amplitude grades was under the frequency of 5 Hz. The vibration times required for the standard preloaded bolts to loosen to a certain extent (using the percentage of the residual preload to the original preload as an indicator) under each displacement amplitude were measured. All bolts in the test were preloaded with the 26 kN preload searched in the standard. After starting the vibration, the test was terminated when the clamping force dropped by 30% or the curve becomes horizontal. The number of valid specimens per displacement amplitude grade was three.

4.1. Experimental Results. The test results under various amplitude grades are shown in Table 3.

It can be seen from the experimental data with amplitude at 0.3 mm that there is a threshold for the vibration amplitude of a certain size of bolt. When the value of vibration amplitude is lower than the value of threshold, the bolt will not completely loosen. It will maintain a certain residual preload and keep vibrating until fatigue fracture. Therefore, based on this experiment, it can be confirmed that the loosening threshold amplitude of the M10 high-strength bolt is about 0.3 mm.

4.2. Loosening Characteristic Curve Rendering. In the logarithmic coordinate system, the curve drawn by the data in Table 3 is shown in Figure 7.

It can be seen that, in the logarithmic coordinate system, the curve basic meets double-line characteristic of the fatigue *S-N* curve. The curve has an obvious inflection point at about 2500 vibration times. Referring to the inflection point of the low-cycle fatigue and high-cycle fatigue in *S-N* curve, it can be approximately believed that the inflection point at 2500 vibration times is also the inflection point of the high-cycle loosening and low-cycle loosening, as shown in Figure 8.

4.3. Curve Expression. With reference to the fatigue material *S-N* curve formula, the section of the straight line in the loosening *D-N* curve can also be expressed with a similar formula:

$$d^m N = C, \tag{2}$$

where m and C are loosening constants.

It can be seen from Figure 8 that the low cycle and high cycle are two lines with different slopes. The dividing point is at amplitude 0.6~0.8 mm with 2500 vibration times. Therefore, the loosening constants of the two straight lines under the three residual preloads can be solved by the data in Table 3. The results are as shown in Table 4.

The summary of the formulas of the loosening *D-N* curves is shown in Table 5.

4.4. Experiment Prospect. In the amplitude 0.3 mm test, it was found that the bolt has not loosened to the predetermined clamping force. Further consideration, referring to the inflection point of ten million times in the fatigue *S-N* curve, it can be predicted that the next dividing point may

Table 3: Loosening vibration times of each amplitude grade.

Amplitude grade	Average vibration times for reaching 90% residual preload	Average vibration times for reaching 80% residual preload	Average vibration times for reaching 70% residual preload
1 mm	12	63	193
0.8 mm	1230	2020	2260
0.6 mm	3265	4725	5150
0.4 mm	8590	10740	11718
0.3 mm	15205	19097	Not achieved

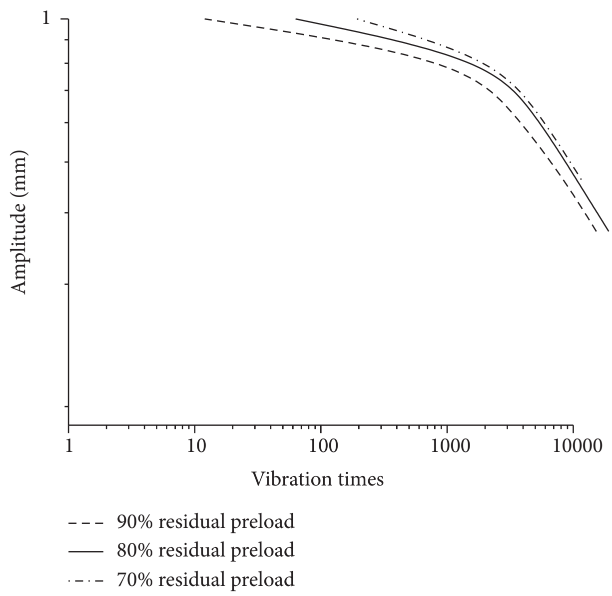

Figure 7: Vibration loosening *D-N* curve in the logarithmic coordinate system.

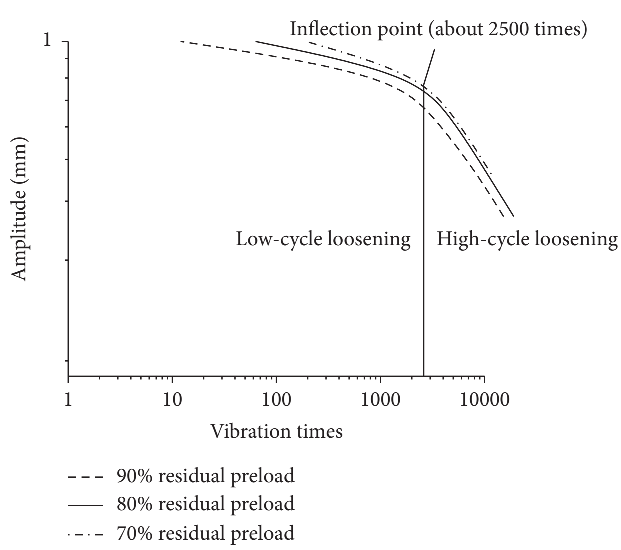

Figure 8: Low-cycle loosening and high-cycle loosening of the loosening *D-N* curve.

exist in a smaller amplitude, which is the infinite life dividing point, or may not exist, as shown in Figure 9. However, this inference needs to be further verified under low displacement amplitude.

Table 4: Loosening *D-N* curve constant solution.

Item	Low cycle 90%	Low cycle 80%	Low cycle 70%	High cycle 90%	High cycle 80%	High cycle 70%
m	20.732	15.526	11.010	2.386	2.028	2.028
C	12.000	63.000	193.000	963.829	1674.943	1825.324

Table 5: Summary of line expressions of the loosening *D-N* curve.

Curve	Expression
Low cycle 90%	$d^{20.732}N = 12$
Low cycle 80%	$d^{15.526}N = 63$
Low cycle 70%	$d^{11.01}N = 193$
High cycle 90%	$d^{2.386}N = 963.829$
High cycle 80%	$d^{2.028}N = 1674.943$
High cycle 70%	$d^{2.028}N = 1825.324$

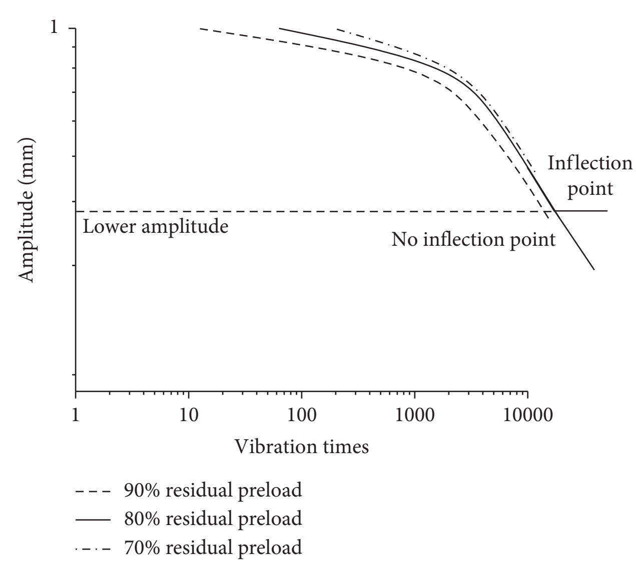

Figure 9: Infinite life dividing point of the loosening *D-N* curve.

5. Cumulative Fatigue Damage Theory and Loosening Accumulation Test Method

As the form of the loosening *D-N* curve is similar to that of the material fatigue *S-N* curve, it is thus believed that the accumulation of bolt looseness has similar accumulation criteria as that of fatigue damage of the material.

In this paper, the simplest linear cumulative fatigue damage theory was used. The theory assumes that the cumulative fatigue damage of materials in different stress levels is separated and independent; the total damage accumulates through linear way. The most representative linear theories are the Miner rule and corrected Miner rule.

5.1. Linear Cumulative Fatigue Damage Theory. The Miner rule makes the following assumption: fatigue damage happens to the specimen when its absorbed energy reaches the limit value. Under this assumption, if the absorbable energy limit before fatigue damage is W, the total cyclic times (total cyclic times under various stress grades) before the specimen damages are N and the absorbed energy at one cyclic time n_1 is W_1, as the proportional relation exists between them, that is:

$$\frac{W_1}{W} = \frac{n_1}{N}. \quad (3)$$

If the loading stresses of specimens are composed of l different stress grades like $\sigma_1, \sigma_2, \ldots, \sigma_l$, fatigue lives under each stress grade are $N_1, N_2, \ldots, N_l$, and cyclic times under each stress grade are $n_1, n_2, \ldots, n_l$, then the total linear cumulative fatigue damage can be expressed as

$$D = \sum_{i=1}^{l} \frac{n_i}{N_i} = 1. \quad (4)$$

When the total damage D reaches the absorbable energy limit value W, fatigue damage will happen to the specimen. Formula (4) is the mathematical expression of the Miner rule. When the critical damage is changed into a constant except 1, it is called as the corrected Miner rule and its mathematical expression is given by

$$D = \sum_{i=1}^{l} \frac{n_i}{N_i} = a, \quad (5)$$

where a is a constant. It can be found in research that it is suggested to take a at 0.7. In this way, the result of life prediction will be safer and more accurate.

5.2. Loosening Accumulation Test Method. A variable amplitude vibration test was designed, and the bolt was subjected to the vibrations of two different displacement amplitudes in the loosening process. It was stipulated that the bigger displacement amplitude was 0.8 mm and the smaller displacement amplitude was 0.6 mm. In the test, two vibration loading orders were set (① "from small to big" and ② "from big to small"). The amplitude in the test was changed when the residual preload decreases to 80%. The values of vibration time were recorded, respectively, when the residual preload reached 80% and reached 70% from 80%.

In the test "from small to big," the vibration times noted as $n_{0.6-1}$ when the residual preload decreased to 80% with displacement amplitude at 0.6 mm. The vibration times note as $n_{0.8-1}$ when the residual preload decreased to 70% from 80% with displacement amplitude at 0.8 mm.

In the test "from big to small," the vibration times noted as $n_{0.8-2}$ when the residual preload decreased to 80% with displacement amplitude at 0.8 mm. The vibration times note as $n_{0.6-2}$ when the residual preload decreased to 70% from 80% with displacement amplitude at 0.6 mm.

It was stipulated in the paper that when the residual preload reached 70%, it was judged that the bolt was loose. The loosening accumulation calculation took the formulas of 70% residual preload in Table 5 as basis. The displacement amplitudes at 0.6 mm belonged to the high-cycle loosening and those at 0.8 mm belonged to the low-cycle loosening. Thus, $N_{0.6} = 5143$ and $N_{0.8} = 2252$ could be calculated based on the expressions in Table 5.

L was defined as the critical loosening with reference to the total damage D in the linear cumulative fatigue damage theory. It could be calculated as

$$L_1 = \frac{n_{0.6-1}}{N_{0.6}} + \frac{n_{0.8-1}}{N_{0.8}}, \qquad L_2 = \frac{n_{0.8-2}}{N_{0.8}} + \frac{n_{0.6-2}}{N_{0.6}}. \quad (6)$$

With reference to the Miner rule, $L = 1$. With reference to the corrected Miner rule, $L = 0.7$. If the results L_1 and L_2 are within the reasonable range of 0.7~1, then the bolt loosening meets the loosening accumulation theory.

6. Test Results of Variable Amplitude Vibration

6.1. Test Results of "from Small to Big". The results of "from small to big" vibration test are shown in Figure 10.

The vibration times of the variable amplitude vibration test "from small to big" at two stages are shown in Table 6.

6.2. Test Results of "from Big to Small". The results of "from big to small" vibration test are shown in Figure 11.

The vibration times of the variable amplitude vibration test "from big to small" at two stages are shown in Table 7.

6.3. Results Analysis. In the test "from small to big,"

$$L_1 = \frac{n_{0.6-1}}{N_{0.6}} + \frac{n_{0.8-1}}{N_{0.8}} = \frac{3730}{5143} + \frac{85}{2252} = 0.763. \quad (7)$$

In the test "from big to small,"

$$L_2 = \frac{n_{0.8-2}}{N_{0.8}} + \frac{n_{0.6-2}}{N_{0.6}} = \frac{1546}{2252} + \frac{1464}{5143} = 0.971. \quad (8)$$

In the vibration test "from small to big," it can be found that the residual preload decreases significantly after the change of the vibration amplitude, which is due to the rapid fracture of bolts after the change, which decreases the residual preload to the minimum, as shown in Figure 12. The residual preload had decreased to 70% before the rapid fracture happened. So the curve is effective for studying loosening. The fracture which leads to the significant reduction of the preload is not the focus. In the vibration test "from big to small," the bolts keep on loosening slowly under vibration and no break happens. In different situations, the critical loosening L may be different, which needs to be determined experimentally. In the two tests, L_1 and L_2 are

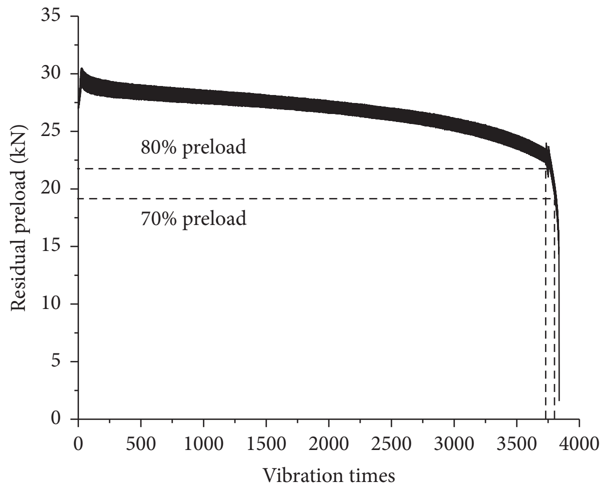

Figure 10: Variable amplitude test loosening curve "from small to big."

Table 6: Variable amplitude test results of "from big to small."

Item	Initial preload (kN)	0.6 mm vibration times when reaching 80% residual preload	0.8 mm vibration times when reaching 70% residual preload
Value	26.95	3730	85

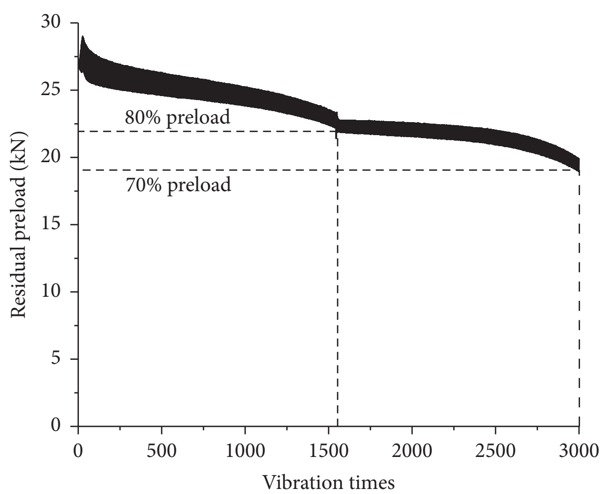

Figure 11: Variable amplitude test loosening curve "from big to small."

Table 7: Variable amplitude test results of "from big to small."

Item	Initial preload (kN)	0.8 mm vibration times when reaching 80% residual preload	0.6 mm vibration times when reaching 70% residual preload
Value	26.95	1546	1464

between 0.7 and 1. According to the theory of Section 5.2, the loosening accumulation of both tests is consistent with the linear loosening accumulation theory. The loosening accumulation under different amplitudes is separated and independent; the bolt loosening accumulates through linear way.

Figure 12: Broken bolt.

7. Conclusions

In this paper, the similarities of the bolt vibration loosening and fatigue were studied through tests and the bolt loosening was studied through the fatigue research.

In the low-frequency vibration, the main physical quantity that controls bolt loosening has been confirmed through variable frequency tests. The conclusion of Junker has been verified.

The vibration loosening situations of the standard preload bolts under each transverse displacement amplitude grade were measured through tests. The test data were drawn into the *D-N* curve characterizing bolt loosening life, and the curve was linearly fitted. The bolt loosening life can be predicted effectively through the *D-N* curve. At the same time, it can be found through this curve that the bolt loosening *D-N* curve and material fatigue *S-N* curve are similar. Both of them are with features of double line and high-cycle and low-cycle inflection point.

Through the variable amplitude test, two variable amplitude vibrations are applied ("from small to big" and "from big to small"). Vibration times at two stages were recorded. Refer to the calculation results of cumulative fatigue damage theory; the numerical results similar to the linear cumulative fatigue damage theory were attained. Therefore, it is believed that there is such a loosening accumulation mechanism of bolts. This method can be used to predict the loosening life in the case of variable amplitude.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Union Project of National Natural Science Foundation of China (nos. U1534209 and 51675446), which are all greatly appreciated.

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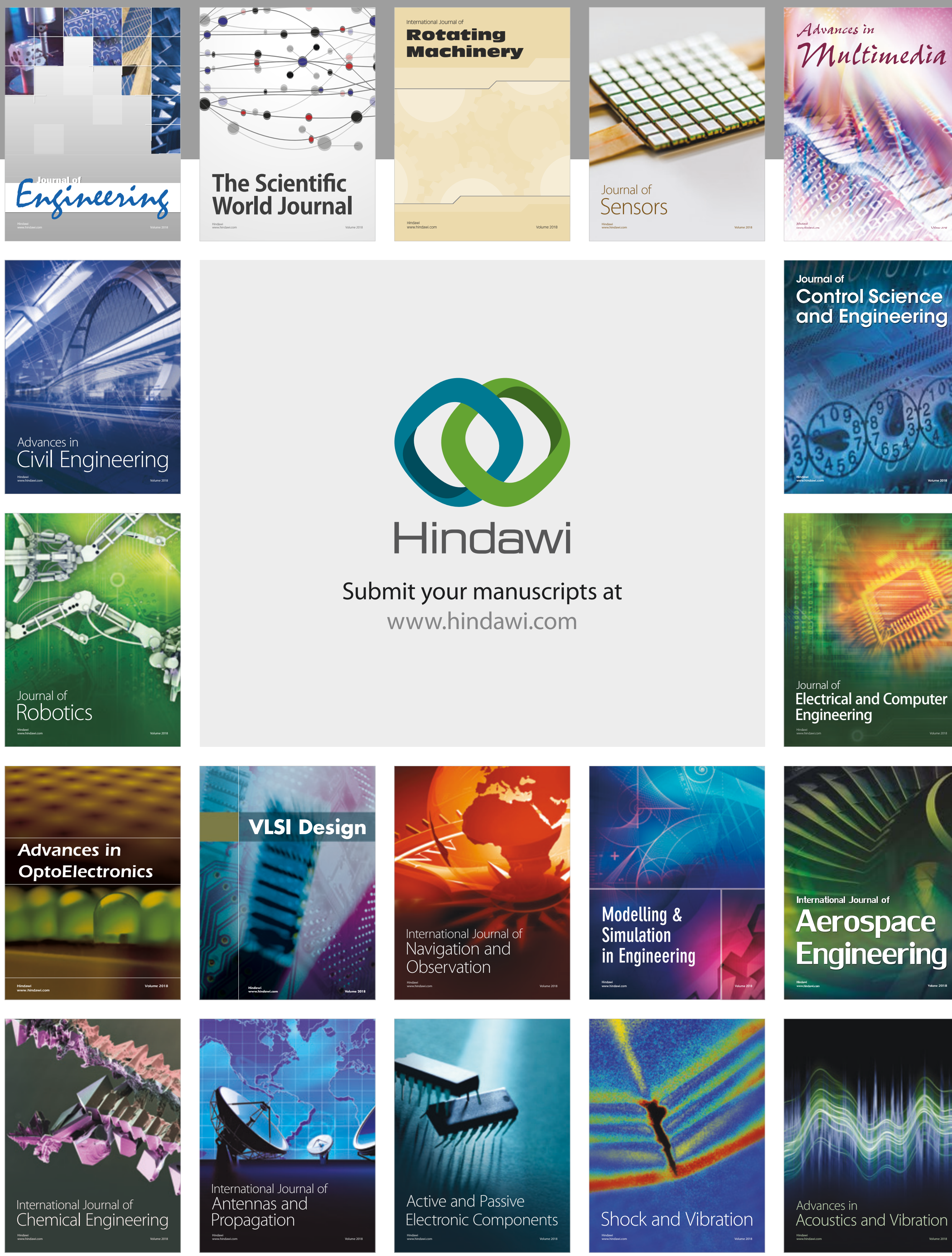
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