Study on Loosening Load Law and Performance of Double Nut of Transmission Tower

Fengkai Ge*,Qinghua Li, Maohua Li, Xinquan Wang

China Electric Power Research Institute Co., Ltd., Beijing 100055, China

*Corresponding author's e-mail: gefk163@qq.com

Abstract. Based on the bolt connection characteristics of transmission tower, this paper studies the loosening mechanism and causes of double nuts of transmission lines. The finite element simulation analysis of bolt connection is carried out by using ABAQUS software.The influence of innitial pretightening force and transverse vibration amplitude on the axial pretightening force of bolt joints and the slip of thread meshing surface is studied.Reducing the initial pretightening force and increasing the transverse vibration amplitude will accelerate the attenuation of axial pretightening force and increase the slip of thread meshing surface.Taking the common nut as the research object, the lateral vibration test of the fastener was completed, and the change trend curve of the axial pretightening force of the bolt was obtained.The anti-loosening performance of equal-thickness double nuts was better than that of other nuts.Aiming at the anti-loosening defects of the existing double nuts, the design of the integrated self-locking double nut is proposed and the lateral vibration test is carried out. The anti-loosening performance index of the integrated self-locking double nut is significantly improved, and the anti-loosening stability is greatly enhanced.

Keywords: power transmission tower; double nut; transverse vibration; numerical simulation;

1 INTRODUCTION

Under the action of static load, the failure of the bolt connection joint is mainly the plastic deformation of the thread part or the fracture of the bolt. However, in practical engineering, transmission towers are often affected by wind, galloping, ice-shedding and other load conditions. At this time, bolted joints are often loose or fatigue failure under dynamic loads such as vibration and impact. Among them, bolt loosening failure is the most common. Loosening of the bolt connection will reduce the bolt pretightening, which will affect the mechanical properties of the joint and even the whole structure, and affect the safety of the structure. At home and abroad, theoretical, simulation and experimental studies have been carried out on the influence of various external factors and structural factors on the loosening process of thread connection. It mainly includes the influence of bolt pretightening, the influence of external transverse load parameters, the influence of bolt connection structure form and size, and the

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influence of surface state of mutual contact in the structure[1].For the bolt connection of transmission tower, under the action of dynamic lateral load, the loosening of bolts is more obvious than that caused by axial load. Summarizing the relevant research on rotational loosening at home and abroad, it can also be found that transverse vibration is the main load form leading to rotational loosening. The study of thread connection loosening under transverse vibration load can be divided into two stages. The first stage is based on the complete slip theory. In the second stage, based on the local slip accumulation theory, JUNKER first found that transverse vibration can lead to serious rotational loosening behavior and a large amount of preload loss in 1969, and proposed the complete slip theory of rotational loosening caused by transverse vibration[2].In 2002, PAI et al.found that the complete slip of the contact interface is not a necessary condition for rotational loosening through finite element simulation and lateral vibration tests. They proposed a local slip accumulation theory that the partial slip region of the contact interface will gradually accumulate with the increase of the vibration period[3]. In order to improve the anti-loosening performance of thread connection and accurately analyze the microscopic process of thread loosening, TANAKAM, YAMAMOTOA and other domestic and foreign scholars have carried out a lot of research through theory and experiment[4]. The research shows that in the threaded connection, the reduction of the pretightening force is earlier than the relative slip between the threaded surfaces. Therefore, it is a feasible method to prevent bolt loosening by studying the change law of the decrease of the pretightening force during the bolt loosening process.At the same time, it is still necessary to use accurate thread connection to establish a mechanical model, and select an accurate model with a spiral structure to help achieve the best simulation results. In this paper, a fine finite element model of threaded connection structure is established. Under the influence of multiple parameters, the static loading simulation and transient dynamic simulation of threaded connection loosening of transmission lines are carried out, and the mechanism of threaded connection loosening is studied. The durability of bolt anti-loosening measures commonly used in transmission towers is poor, and professional bolt anti-loosening products are still in the preliminary pilot application stage in transmission lines. Therefore, we urgently need to combine finite element simulation analysis and experimental research to explore the law of bolt loosening load of transmission tower and improve the existing bolt loosening prevention measures.

2 LOOSENING MECHANISM OF DOUBLE NUTS

The tightening torque of the bolt is used to overcome the friction torque between the nut and the bolt thread and the end face friction torque between the nut and the supporting surface of the connector. The calculation formula of the tightening torque is :

$$T = T_1 + T_2 = \frac{P}{2} d_2 \tan(\lambda + \rho_v) + \frac{P}{2} \mu_1 d_m = \frac{P}{2}[d_2 \tan(\lambda + \rho_v) + \mu_1 d_m] \tag{1}$$

T—Tightening torque of bolt,N·m;

T_1—Thread friction torque,N·m;

T_2—Friction torque of nut bearing surface,N·m;

P—Bolt pretightening,kN;
λ — Helix angle,°;
ρ_v—Thread equivalent friction angle,°;
μ_1—Friction coefficient of nut bearing surface;
d_2—pitch diameter of thread,mm;
d_m—Average diameter of nut bearing surface,mm.

The torque control method is the most initial and simplest control method. It is based on the linear proportional relationship between the axial pretightening of the bolt and the tightening torque when the threaded connection is tightened[4]. This proportional coefficient is defined as the torque coefficient. The torque coefficient is an empirical coefficient that directly reflects the relationship between torque and axial pretightening during bolt tightening. It is a necessary and key parameter for tightening. The torque coefficient is taken as :

$$K=\frac{1}{2}[\frac{d_2}{d}\tan(\lambda+\rho_v)+\frac{d_m}{d}\mu_1] \tag{2}$$

The calculation formula of bolt tightening torque is：

$$T=K\cdot P\cdot d \tag{3}$$

K—torque coefficient;
d—Thread nominal diameter， mm;

Taking d2/d=0.92,λ=2.5°,=10°,dm/d=1.3,μ1=0.15, the torque coefficient can be approximately taken.

$$\begin{aligned}K&\approx\frac{d_2}{2d}\tan\lambda+\frac{d_2}{2d}\tan\rho_v+\frac{d_2}{2d}\mu_1\\&\approx0.0201+0.0811+0.0975\approx0.2\end{aligned} \tag{4}$$

From the above calculation, it can be seen that the torque coefficient can be approximately 0.2 for the general ordinary thread connection. According to the formula 4, the tightening torque is composed of three parts. The first part is generated by the thread angle, which produces the pretightening that makes the bolt rod elongate. The second part is the friction of the thread pair, which accounts for about 40%. The third part is the friction of the support surface, which accounts for about 50%, and the latter two account for about 90%[5]. Since about 90% of the tightening torque is consumed by the friction torque of the thread and the support, only 10% is converted to the clamping force. The innitial pretightening force changes with factors such as friction loss during tightening, so the dispersion is large.

If the fastener is likely to experience cyclic loading, the role of preload becomes to limit the amplitude of cyclic loading on the fastener to below the endurance limit. The application of a proper amount of preload has been repeatedly emphasized as a safety measure against bolts fatigue failure with most of bolt fatigue failures being associated with either inadequate or excessive preload[6-8]. However, Under a certain lateral vibration load, it is basically impossible to achieve reliable anti-loosening by simply relying on the friction force of the contact surface between the nut and the bolt thread. Due to the randomness of the magnitude, direction and frequency spectrum of the transverse load, no matter how large the friction force generated by the innitial pretightening force of the thread contact surface is, with the action of a certain amplitude of the transverse load on the connecting pair, it will gradually relax and eventually fail under the combined action of deformation and loosening trend force.

3 NUMERICAL SIMULATION ANALYSIS OF NUT LOOSENING

In this paper, Matlab software is used to calculate the node number, node coordinates and unit number of the thread part. The modeling of the screw part is completed in ABAQUS software. Finally, the accurate model of the bolt is established by Boolean operation. The finite element model of the nut is established by the same method. Finally, the bolt, the clamping block and the nut are assembled to form an accurate model of the bolt connection structure. Bolt pretightening and periodic displacement loading are applied in different analysis steps. At present, the most commonly used bolts for transmission lines are 6.8M16, 6.8M20 and 8.8M24.In this paper, the representative 6.8M20 bolt connection is selected as the research object of numerical analysis.Because the galloping vibration of transmission tower is the main cause of bolt loosening, the tower galloping frequency is low, and the transverse vibration process of bolts is a quasi-static process. The dynamic effect is not obvious. Under the same number of vibrations, the vibration frequency has little effect on the reduction ratio of bolt pretightening, and the bolt loosening behavior is mainly related to the number of transverse vibrations. Relevant experimental research and numerical simulation studies have also been confirmed. Therefore, this paper only analyzes the influence of two key parameters, innitial pretightening force and vibration amplitude, on bolt loosening.

In order to verify the validity of the established hexahedral finite element model, the simulation data are compared with the lateral vibration test of 6.8M20 single nut. The comparison between the simulated data (average preload) and the experimental data under the same vibration condition is shown in Figure 1. It can be seen from the diagram that the simulated data and the experimental data are in good agreement, which can verify the validity of the established full hexahedral finite element model.

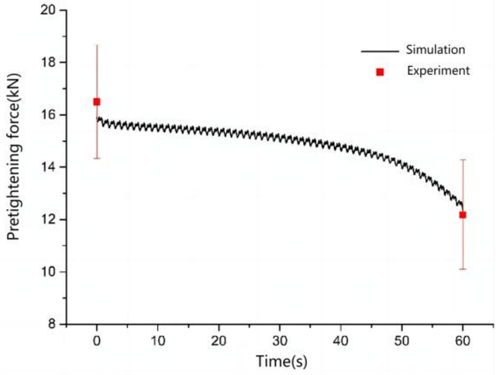


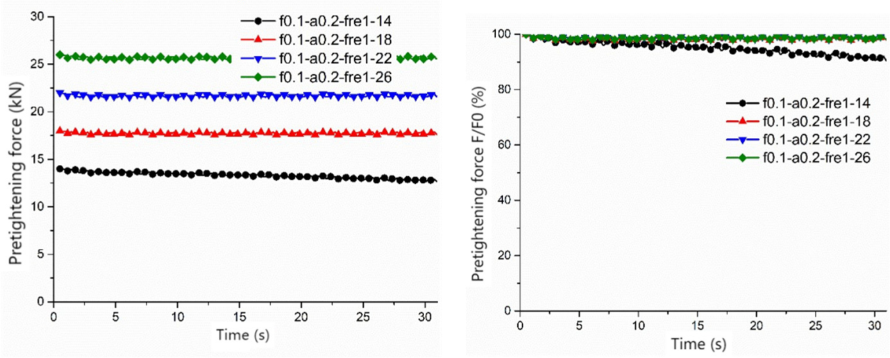
Fig. 1. Comparison of test data and simulation data (f=1Hz,S=0.2mm,μ=0.1).

3.1 Analysis of the Influence Of Initial Pretightening Force

The 6.8M20 bolt is selected under the action of four different initial pretightening force of 14kN,18kN,22kN and 26kN. According to different lateral vibration amplitudes (0.1mm,0.2mm,0.3mm,0.4mm), the same friction coefficient (0.1) and vibration frequency (1Hz), the numerical simulation calculation of bolt loosening is carried out according to the same vibration times.The variation curves of bolt axial force and nut rotation angle with vibration time are proposed.

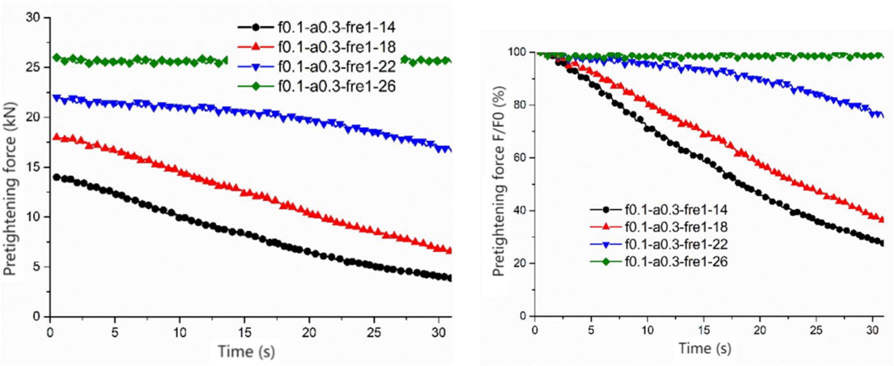
3.1.1.Analysis of Bolt Axial Force Variation Under Different Innitial Pretightening Forces.

Through the numerical calculation of loosening of 6.8M20 bolt after fastening according to four different initial pretightening force, the calculation results of the same three influencing parameters of transverse vibration frequency, vibration amplitude and friction coefficient are compared. The analysis of bolt pretightening force results is shown in Figure 2 to Figure 4.



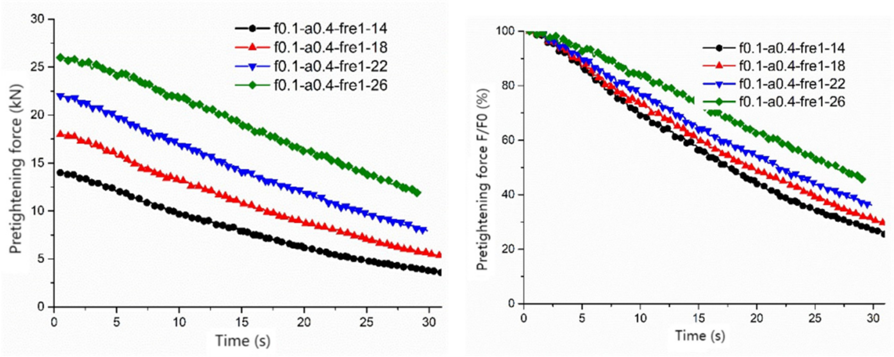
(a)Axial pretightening force (b)Residual pretightening force ratio

Fig. 2. Bolts under different initial pretightening force(f=1Hz,S=0.2mm,μ=0.1).



(a)Axial pretightening force (b)Residual pretightening force ratio

Fig. 3. Bolts under different initial pretightening force(f=1Hz,S=0.3mm,μ=0.1).



(a)Axial pretightening force (b)Residual pretightening force ratio

Fig. 4. Bolts under different initial pretightening force(f=1Hz,S=0.4mm,μ=0.1).

From the figure, it can be seen that when other influencing factors remain unchanged, after the same number of vibrations, the smaller the innitial pretightening force of the bolt, the faster the axial force of the bolt decreases, and the smaller the ratio of the residual pretightening to the innitial pretightening force, indicating that the bolt is easier to loosen.

3.1.2.Analysis of Thread Meshing Surface Slip Under Different Innitial Pretightening Forces.

A path is selected along the circumferential direction of the thread, as shown in Figure 5. The distribution of the slip amount of the thread meshing surface along this path under different axial pretightening force is shown in Figure 6.

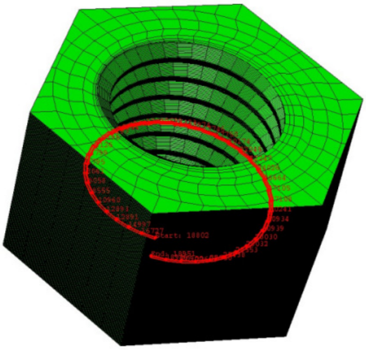
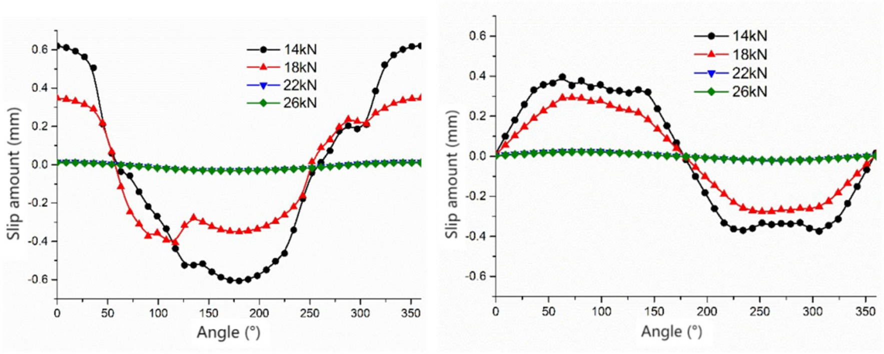


Fig. 5. Thread circumferential path.

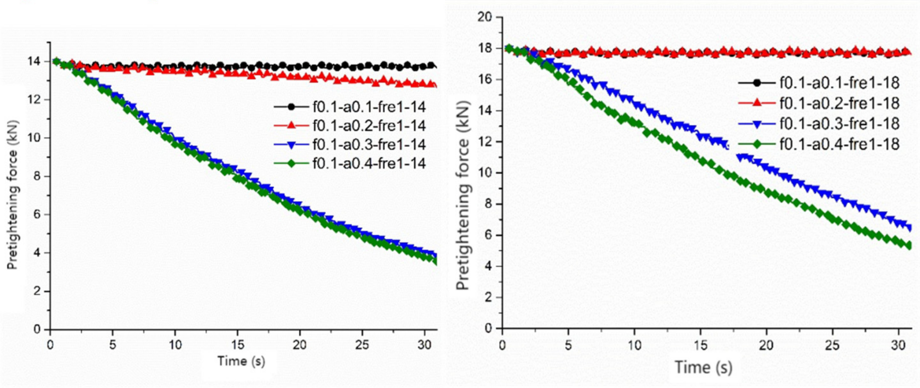


(a)Slip amount in X-axis direction (b)Slip amount in Y-axis direction

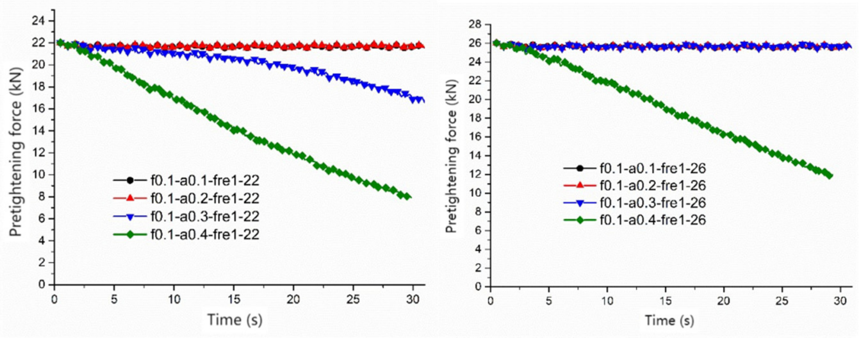
Fig. 6. Thread slip amount under different initial pretightening force(f=1Hz,S=0.2mm,μ=0.1).

3.2 Analysis of the Influence of Transverse Vibration Amplitude

The 6.8M20 bolt was selected under the action of four different transverse vibration amplitudes of 0.1mm, 0.2mm, 0.3mm and 0.4mm.According to different innitial pretightening forces (14kN, 18kN, 22kN, 26kN), the same friction coefficient (0.1) and vibration frequency (1Hz), the numerical simulation of bolt loosening was carried out according to the same vibration times. The variation curves of bolt axial force and nut rotation angle with vibration time were proposed.The analysis of results is shown in Figure 7 to Figure 9.



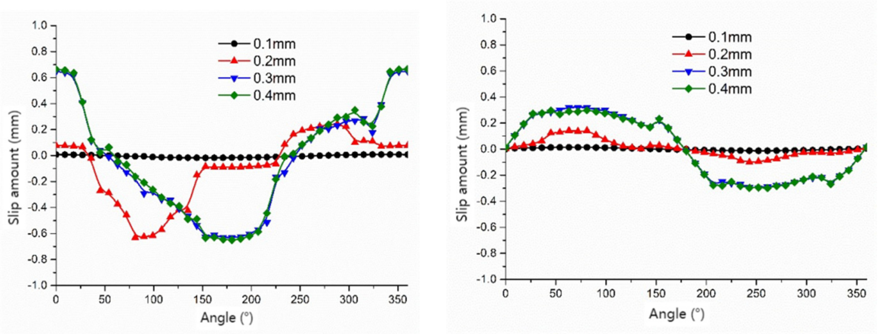
(a)Pretightening force 14kN (b)Pretightening force 18kN



(c)Pretightening force 22kN (d)Pretightening force 26kN

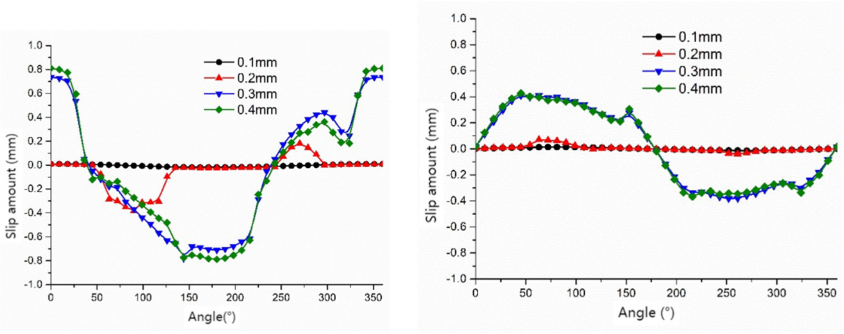
Fig. 7. Bolt pre-tightening force under different lateral vibration amplitude(f=1Hz,μ=0.1).

When the lateral vibration amplitude is less than a certain critical value, the bolt is basically not loose ; when the transverse vibration amplitude is greater than a critical value, the greater the transverse vibration amplitude, the faster the axial force of the bolt decreases, and the smaller the ratio of the residual pretightening to the innitial pretightening force, indicating that the bolt is easier to loosen.



(a)Slip amount in X-axis direction (b)Slip amount in Y-axis direction

Fig. 8. Thread slip amount under different lateral vibration amplitude(P=14kN,f=1Hz,μ=0.1).



(a)Slip amount in X-axis direction (b)Slip amount in Y-axis direction

Fig. 9. Thread slip amount under different lateral vibration amplitude(P=18kN,f=1Hz,μ=0.1).

It can be seen that the larger the transverse vibration amplitude is, the larger the slip amplitude of the inner and outer thread meshing surface of the bolt and nut is, indicating that it is easier to loosen. When the transverse vibration amplitude is very small, the thread meshing surface does not slip, or only local slip occurs. These two cases will not cause the nut to rotate, and will not cause the bolt to loosen obviously.

4 DOUBLE NUT VIBRATION EXPERIMENTAL DATA ANALYSIS

4.1 Vibration Experimental Analysis of Double Nuts

In order to detect the anti-loosening performance of double nuts, this paper refers to the Chinese standard 'Fastener Transverse Vibration Test Method' (GB/T10431-2008), and selects 6.8M20,8.8M24 bolts commonly used on transmission lines. There are 10 samples in each group for double nut test, 5 samples in each group for double nut to increase the torque test of the outer nut. The test conditions are as follows : the test frequency is 10 Hz ; No-load amplitude: ± 1.6mm for M16 bolts,± 1.9mm for M20 bolts and ± 2.0mm for M24 bolts; the lubrication condition is oil [9-10].The analysis of bolt pretightening force results is shown in Table 1.

Table 1. Common nut transverse bolt vibration test table.

Type	Specification	Number of nut	Vibration times	Residual /Initial	Standard deviation	Installation torque /(N.m)	Remark
Spring washer	6.8M16	3	1800	16.70%	19.50%	80	Standard torque
	6.8M20	3	1800	5.90%	3.20%	100	
Securing gear nut	6.8M16	3	1800	24.20%	20.40%	80	Standard torque
	6.8M20	3	1800	8.10%	6.10%	100	
Single nut	6.8M20	5	3000	27.60%	11.60%	100	Standard torque
	8.8M24	5	3000	5.60%	10.10%	250	
Equal thickness double nut	6.8M20	10	3000	26.30%	12.50%	102/51	The torque of the outer nut is half of the inner nut.
	8.8M24	10	3000	30.40%	11.80%	252/126	
	6.8M20	10	3000	27.00%	17.40%	104/102	The torque of inner and outer nuts is the
	8.8M24	10	3000	34.20%	15.10%	252/252	

							same
	6.8M20	5	3000	36.30 %	8.70%	100/220	Increase the torque of the outer nut
	8.8M24	5	3000	13.90 %	13.70%	250/380	
Thick nut + thin nut	6.8M20	10	3000	21.00 %	14.50%	103/51	The torque of the outer nut is half of the inner nut.
	8.8M24	10	3000	12.30 %	11.40%	252/125	

From the transverse vibration test data, it can be seen that the double nut has better anti-loosening performance than the spring washer and the fastening nut. Compared with single nut and one thick and one thin double nut, the anti-loosening performance of equal thickness double nut bolt is improved. Increasing the tightening torque of the outer nut, the improvement of the anti-loosening performance of the double nut is not obvious.

4.2 Vibration Experiment of New Integrated Self-locking Double Nut

As shown in Figure 10, the integrated self-locking double nut (referred to as 'integrated self-locking nut') in power transmission and transformation engineering applies the eccentric self-locking principle of nut and screw. The lateral pressure P3 generated by the screw is completely generated by the eccentric structure of the upper and lower double nuts, which is not affected by the installation torque of the lower main nut. Even if the pretightening force of the lower nut completely disappears, the lateral pressure P3 will not be weakened. When the integrated self-locking nut is fastened, the locking force generated by the mechanical eccentric structure of the upper and lower double nuts.

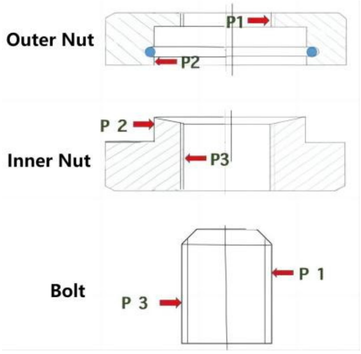


Fig. 10. Integrated self-locking double nut.

The transverse vibration is accelerated under the same test conditions, and the ratio of the residual pretightening to the innitial pretightening force of the bolt is tested. After the same number of vibrations, the higher the ratio of the 'residual pretightening force / innitial pretightening force' of the bolt is, the better the anti-loosening performance of the bolt is. Two kinds of bolts, 6.8M20 and 8.8M24, which are commonly used in transmission lines, are selected, with 10 samples in each group. The test conditions are as follows : the test frequency is 10 Hz ; No-load amplitude: ± 1.6mm for M16 bolts, ± 1.9mm for M20 bolts and ± 2.0mm for M24 bolts ; vibration 3000 times.The analysis of bolt pretightening force results is shown in Table 2.

Table 2. Transmission line nut transverse vibration test data summary table.

Type	Installation method and torque value/(N.m)		Specification	Residual axial force ratio/(%)					Standard deviation
				0	750	1500	2250	3000	
Single nut	Standard torque	100	6M20	100.00%	44.80%	42.30%	39.80%	27.60%	11.60%
		250	8M24	100.00%	17.10%	10.80%	9.30%	5.60%	10.10%
Equal thickness double nut	Lower nut / upper nut=100%/ 50%	(100/50)	6M20	100.00%	33.40%	30.20%	27.80%	26.30%	12.50%
		(250/125)	8M24	100.00%	66.80%	56.20%	43.60%	30.40%	11.80%
Thick nut + thin nut		(100/50)	6M20	100.00%	27.30%	23.10%	21.80%	21.00%	14.50%
		(250/125)	8M24	100.00%	27.80%	20.60%	15.90%	12.30%	11.40%
Integrated self-locking nut	The upper nut rotates 60 degrees	(80/146)	6M16	100.00%	85.40%	81.10%	78.90%	77.40%	7.40%
		(100/218)	6M20	100.00%	88.90%	85.80%	84.40%	83.70%	2.10%
		(250/340)	8M24	100.00%	94.70%	86.60%	83.10%	80.00%	4.80%

The test results show that : Compared with the equal thickness double nut, the average value of 'bolt residual axial force / initial pretightening force' reflecting the anti-loosening performance index of the integrated self-locking nut is increased from 26.3% to 83.7% for 6.8M20 bolts, which is increased by 2.18 times. For the 8.8M24 bolt, it increased from 30.4% to 80.0%, an increase of 1.63 times. The 'standard variance' reflecting the discreteness of the anti-loosening performance is also reduced to less than 10%, indicating that the consistency of the anti-loosening performance is better and the anti-loosening performance is more stable.

5 CONCLUSION

In this paper, the numerical simulation experiment of bolt connection loosening of transmission tower and the transverse vibration experiment of double nuts are carried out to determine the vibration characteristics of bolt connection of transmission tower and the influence of innitial pretightening force on residual pretightening and anti-loosening performance of bolts. The anti-loosening effect of double nut bolts of transmission tower under transverse vibration is evaluated. The main conclusions are as follows :

Under the transverse vibration load of the transmission tower, it is not reliable to simply increase the friction force as the anti-loosening condition. The key to the double nut anti-loosening is to produce a jacking force between the inner and outer nuts, so as not to be affected by the reduction or loss of the bolt pretightening of the connecting part, and to better play the self-locking anti-loosening ability of the double nut.The smaller the axial pretightening is, the larger the slip of the thread meshing surface is, and the easier the bolt is to loosen. On the contrary, the bolt is not easy to loose. When the axial pretightening force reaches the critical pretightening force, the thread meshing surface basically does not slip, and the bolt basically does not loosen. The larger the transverse vibration amplitude is, the larger the slip amplitude of the thread meshing surface is, the larger the rotation angle of the bolt and nut is, and the easier the bolt is to loosen. When the transverse vibration amplitude is less than a critical value, the thread meshing surface does not slip, or only local slip occurs. These two cases will not cause the nut and bolt to rotate, and will not cause the bolt to loosen obviously.Compared with the single nut, equal thickness double nut and one thick and one thin double nut commonly used in transmission towers, the integrated self-locking nut has a greatly improved anti-loosening performance, good anti-loosening performance and relatively stable anti-loosening performance.The research results are of great significance for improving the overall level of transmission line bolt anti-loosening technology, improving the safety and reliability of transmission line body structure, and reducing the workload of operation and maintenance.

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REFERENCE

1. Mo Z. (2022). Research on Loosening Mechanism of Bolt Connection under Transverse Load(Master degree thesis,North China Electric Power University).
2. Wu J, Liao R D & Ding X Y. (2019). Research on Prediction of Lateral Loose Life of Threaded Connection Structure and Its Influencing Factors. Structure & Environment Engineering,46(2),7.
3. Pai, N., & Hess, D.P. (2002). Experimental Study of Loosening of Threaded Fasteners due to Dynamic Shear Loads. Journal of Sound and Vibration, 253, 585-602.
4. Li R Y. (2019). The Control Method of Bolt Tightening Robot on Power Transmission Lines(Doctoral dissertation,Changsha University of Science and Technology).
5. Qiao Y J,Zhou F.C.,Lv L. & Han Y. (2014). Analysis of Pretighting of Bolts for Composite Piston. Internal Combustion Engine & Powerplant,31(6), 3.
6. Cho, S. S., Chang, H., & Lee, K. W. (2009). Dependence of fatigue limit of high-tension bolts on mean stress and ultimate tensile strength. International journal of automotive technology, 10, 475-479.
7. Casanova, F., & Mantilla, C. (2018). Fatigue failure of the bolts connecting a Francis turbine with the shaft. Engineering Failure Analysis, 90, 1-13.

8. Jawwad, A. K. A., ALShabatat, N., & Mahdi, M. (2021). The effects of joint design, bolting procedure and load eccentricity on fatigue failure characteristics of high-strength steel bolts. Engineering Failure Analysis, 122, 105279.
9. Yang F L, Li Z, Zhang D C. (2018). Experimental study on the transversal vibration of double-nut bolted joints of transmission towers. Journal of Vibration and Shock, 37(10), 164-171.
10. Li, Q., Li, M.H., Wu, J., Liu, Y., & An, P. (2023). Experimental study on anti-loosening technology of transmission line bolts. Journal of Physics: Conference Series, 2557.