OPTIMIZATION ON THE PERFORMANCE OF A PRECISION FLANK-LOCKING LOCKNUT CONSIDERING THE MACHINING AND OPERATIONAL PARAMETERS

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ABSTRACT

In this study, the anti-loosening characteristics of a precision flank-locking locknut fabricated under various machining processes and tested in different dynamic environments were investigated. The control parameters considered include the tightening torque and thread pitch of the set screw, machining process on the end plane of locknut, and vibration amplitude and frequency of dynamic loading in service, etc. Their sensitivities on the axial force ratio and anti-loosening ratio of the locknut were evaluated using Taguchi method. It was found that the pretension of locknut, the tightening torque and the pitch of set screw, and the machining process of the nut's end plane were the significant control parameters for the anti-loosening performance of the locknut. Moreover, the results of experimental measurements were employed in the regression fit on the performance of the locknut. The regression model was able to predict the anti-loosening ratio with 4.42% average error comparing with the measurements. Furthermore, the optimized design of the locknut through the Taguchi method was able to increase the axial force ratio and anti-loosening ratio by 20.4% and 16.8%, respectively, comparing with standard locknut.

Keywords: Flank-locking locknut, Taguchi method, Anti-loosening ratio, Regression analysis.

1. INTRODUCTION

The flank-locking locknut has been extensively employed in the spindle assembly for modern machine tools. With the machine tools evolve into high speed machining, high precision, specialized and customized design, the performance and reliability of the key components becomes more critical. Among them, the advancements in spindle technology are believed to determine the breakthrough in the machine tool industry. More specifically, the locknut for the spindle can play an important role in the assurance of the precision and reliability of the machinery.

Sase and coworkers [1] designed both displacement-based and acceleration-based testing methods for the evaluation of seven types of anti-loosening nuts. They concluded that only the nut with an internal taper could slow the loosening process considerably. Both the relative sliding on the contact surfaces between threads of nut and bolt, and the end plane between nut and workpiece was found to be the major mechanism of fastener loosening [2]. Therefore, an improved design called step-lock-bolt (SLB) was proposed by Sase and Fuji [3] to counteract the sliding between thread contact surface. It should be noted that if either one of the relative sliding is impeded, the loosening of the nut can be prevented.

A testing equipment which is capable of measuring torque and axial force of a tightened fastener was reported by Eccles *et al* [4]. It was used to study the variation of friction coefficient of zinc-plated nut in repeated tightening and loosening operations. At the first four times of operations, the friction coefficient increased gradually. However, the friction coefficient reached stable level after the fifth operation. Nassar and coworkers [5] tested the influences of lubrication and tightening speed on the tightening constant. They found that with the tightening speed lower than 30 rpm,

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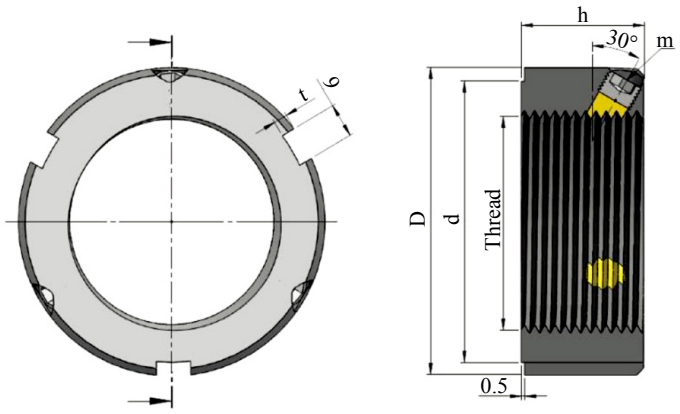
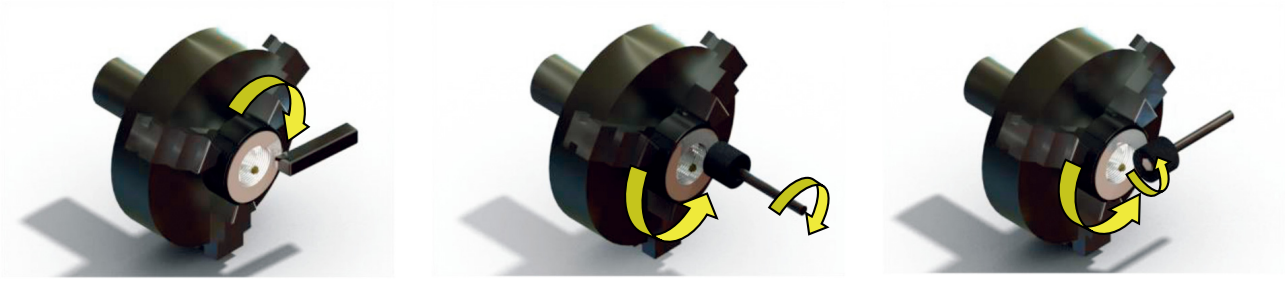


Fig. 1 The schematic configuration of the flank-locking locknut used in this study.



(a) (b) (c)

Fig. 2 Schematic diagrams for three different machining processes of the collar surface: (a) fine turning, (b) cross grinding, (c) concentric grinding.

the tightening constant and friction coefficient grew larger with repeated operation. On the other hand, with lubrication the tightening constant decreased drastically. When the tightening speed was over 30 rpm, the wear caused by the repeated operation was alleviated. Reid and Hiser [6] reported that the tightening torque and its induced axial pretension force were crucial in the sliding of the fastened parts. According to the standard ASTM F606-95b, Hess and coworkers [7] investigated the strength of the fastener parts. They reported that, with a reduction in pitch and outer diameter of the bolt, the higher induced stress decreased both the yielding and ultimate strengths of the fastener. Similarly, both strengths of the fastener reduced while the pitch and inner diameter of the nut increased.

Among the relevant studies in the design of locknut, the one devoted to the flank-locking locknut was rarely found. The flank-locking locknut has been widely employed in the spindle assembly for high speed machine tools. However, the design methodology and the key parameters which control the anti-loosening characteristics of this type of locknut have not been well studied. Therefore, in this study, the anti-loosening characteristics of a precision flank-locking locknut fabricated under various machining processes and tested in different dynamic environments were investigated.

2. EXPERIMENTAL

2.1 The Flank-Locking Locknut

The flank-locking locknut used in this study is shown in the schematic drawing of Fig. 1. The locknut was made of CrMo alloy steel SCM 440 and the thread was precision ground with 5h tolerance grade of ISO 965-3 [8]. There were three set screws, made of SCM 435 and complied to the regulation of ISO 4026 [9], equal-spaced circumferentially and inclined 30° in the radial direction. In front of each set screw, a copper pad which was made of phosphorus bronze C5441 provided a softer contact between the locknut thread and the set screw. One end of the locknut was machined to a diameter d which served as the contact collar with the clamped object. Three different machining processes for the collar surface were evaluated in this study: fine turning, cross grinding and concentric grinding, as schematically shown in Fig. 2.

Before the detail in the experimental planning is introduced, several quantitative measures of the anti-loosening characteristics of this flank-locking locknut are defined first. The anti-loosening torque ratio T_r is defined as:

$$T_r = \frac{T_L}{T_F}. \quad (1)$$

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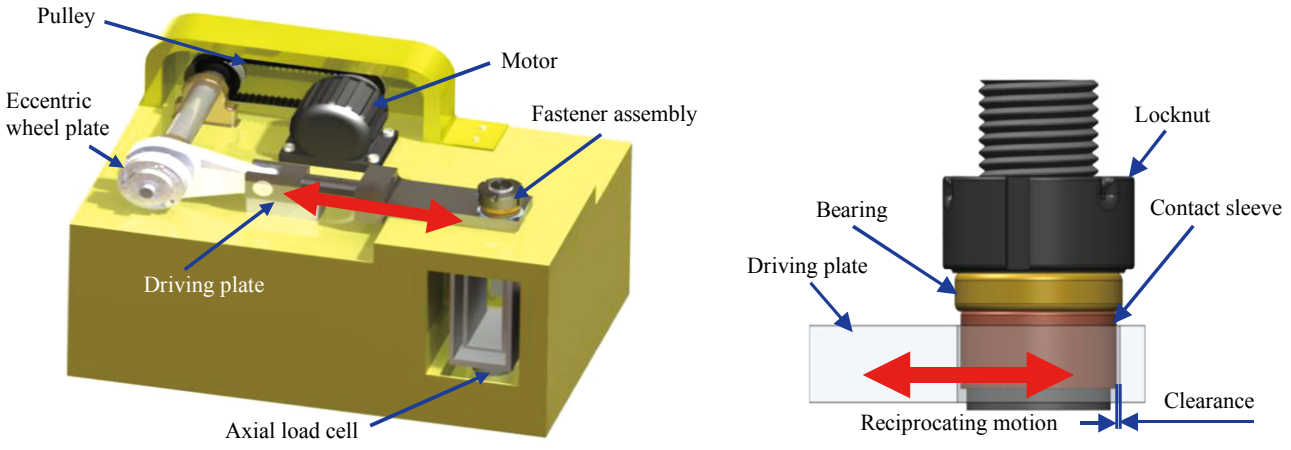


Fig. 3 The schematic setup for the dynamic testing of the fastener assembly: (a) whole setup, (b) details at the locknut.

In the above equation, T_F denotes the initial tightening torque on the locknut required to generate the desired axial pretension $F_{initial}$ in the fastener, which is measured by the axial load cell assembled at the bottom of the locknut assembly as denoted in Fig. 3(a). After the nut is tightened, the set screws are tightened evenly to the prescribed torque. The fastener setup then subjects to dynamic testing with specified parameters, such as vibration amplitude and frequency etc. After the preset number of cycles has been completed, the torque required to loosen the locknut from the assembly T_L is measured. In the meantime, an axial force ratio is defined as the ratio of axial tension in the fastener assembly before and after the dynamic test, which can be written as:

$$F_r = \frac{F_{final}}{F_{initial}} \tag{2}$$

2.2 Setup for the Dynamic Testing of Fastener Assembly

The dynamic tester employed in this study was designed, following the design by Junker [10], and built in-house and its schematic diagram is presented in Fig. 3(a). The driving rotational power from the motor was transmitted through the pulley system to the eccentric wheel plate, which transformed the rotation into reciprocating motion of the driving plate. The frequency and amplitude of the reciprocating motion of the driving plate could be adjusted by the motor speed and the eccentricity of the eccentric wheel, respectively. The reciprocating linear motion of the driving plate generated a periodic impact on the contact sleeve in the fastener assembly due to the preset 1-mm clearance between them, as shown in Fig. 3(b). This lateral impact induced dynamic loading and vibration on the fastener assembly. Under the influence of these periodic loadings at selected frequency, the axial tension in the fastener assembly could gradually deteriorate and lower the anti-loosening torque of the locknut.

When the flank-locking locknut was mounted on the test fixture, a digital torque wrench (FUTEK－TAT510) was used to measure the tightening torque. The measured signal was processed through a data processing module (KYOWA-DBU-120A) and recorded on a personal computer. Then, the tightening of the three set screws was carried out in three steps and in alternating sequence. A preset torque wrench (KANON－120QL K) was employed in this stage. More specifically, if the final tightening torque was T_f, the maximum torque for each step was set to $T_f/3$, $T_f/2$ and T_f, respectively. In addition, the tightening sequences for the three set screws in these steps were (1,2,3), (3,2,1) and (1,2,3). These precautious measures were adopted to minimize the unevenness in locknut mounting during the assembly of the fastener.

Although the preload of the fastener can usually be stabilized after 1000 cycles of impact vibration test [10], the long term degradation in preload is still very critical for certain applications. Therefore, the fastener assembly was gone through a total of 20,000 times impact test. The loosening torque T_1 of the fastener assembly after dynamic testing was also measured by using the aforementioned digital torque wrench. Fitted with the right connector and socket, the wrench was loaded gradually in counterclockwise direction. The unloading torque was recorded until the fastener assembly loosened.

2.3 Experiment Planning

Taguchi method has been an efficient and reliable method for improving the quality of a design or process [11]. A variety of parameters which occur in manufacturing process and design phase can all be taken into account in this systematic design approach. Moreover, the influence due to the interaction of parameters can also be accounted. Therefore, Taguchi method is adopted in this study to find the important factors which control the anti-loosening characteristics of the flank-locking locknut. However, the obtained optimal design should be reassured with the confirmation test [12].

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Table 1 The factors and levels used in the experiment planning of this study.

Factor	Level 1	Level 2	Level 3
A. axial pretension (kN)	4.9	9.8	14.7
B. impact frequency (Hz)	13.33	16.67	20.0
C. displacement amplitude of the driving plate (mm)	±1.2	±1.3	±1.4
D. tightening torque for set screw (N·m)	2.55	5.88	7.65
E. thread pitch of set screw (mm)	1.0	1.5	2.0
F. machining of collar surface	Cross grinding	Fine turning	Concentric grinding
G. fit clearance of nut (mm)	+0.03	+0.2	+0.5

Table 2 $L_{18}(3^7)$ orthogonal array for the selected experiments.

Sample	A	B	C	D	E	F	G
T1	1	1	1	1	1	1	1
T2	1	2	2	2	2	2	2
T3	1	3	3	3	3	3	3
T4	2	1	1	2	2	3	3
T5	2	2	2	3	3	1	1
T6	2	3	3	1	1	2	2
T7	3	1	2	1	3	2	3
T8	3	2	3	2	1	3	1
T9	3	3	1	3	2	1	2
T10	1	1	3	3	2	2	1
T11	1	2	1	1	3	3	2
T12	1	3	2	2	1	1	3
T13	2	1	2	3	1	3	2
T14	2	2	3	1	2	1	3
T15	2	3	1	2	3	2	1
T16	3	1	3	2	3	1	2
T17	3	2	1	3	1	2	3
T18	3	3	2	1	2	3	1

The goal of this study is to explore the optimal design of the locknut having maximum anti-loosening characteristic under various testing conditions. Thus, the object function will be maximized and the S/N ratio for each selected parameter will be examined through the analysis of variance (ANOVA).

According to the experiences collected from the manufacturer, seven significant factors which could dominate the anti-loosening characteristics of this flank-locking locknut were identified. In addition, three levels for each parameter were selected for a locknut with D = 45 mm, d = 40 mm, h = 18 mm, g = 5 mm, t = 2 mm, and M6 set screws. Table 1 presents the factors and corresponding levels investigated in this study. The corresponding $L_{18}(3^7)$ orthogonal array for the selected experiments is depicted in Table 2.

2.4 Regression Fit for the Anti-Loosening Characteristics

In order to establish a performance function of the flank-locking locknut, the testing results from the 18 samples were employed in a regression fit procedure. Before the regression function can be assumed, all the factors should be in numeric quantities. It is realized that all the factors selected in Table 1 comply with this requirement except the factor F- machining process. Therefore, a numeric value which can describe the difference in different machining processes was proposed. Table 3 lists the measured surface roughness Ra for the three different machining processes. It seems that the fine turning surface had the highest Ra while concentric grinding provided the smoothest surface finish. It was coincided with the knowledge from common practice.

With the surface roughness as a substitute for the machining process factor, the regression fit of the object function could be preceded. For simplicity, the dependence of the object function on the factors was assumed to be quadratic and the coupling among the factors was neglected. These assumptions will be checked with the verification example presented later in this study. Thus, the regression function Y is written as:

$$Y = \sum_{i=A}^{G} (c_{i2} X_i^2 + c_{i1} X_i) + c_0 \tag{3}$$

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Table 3 The measured roughness Ra for the collar surface machined with different processes.

Machining process	Roughness, Ra (μm)
Cross grinding	0.434
Fine turning	0.687
Concentric grinding	0.145

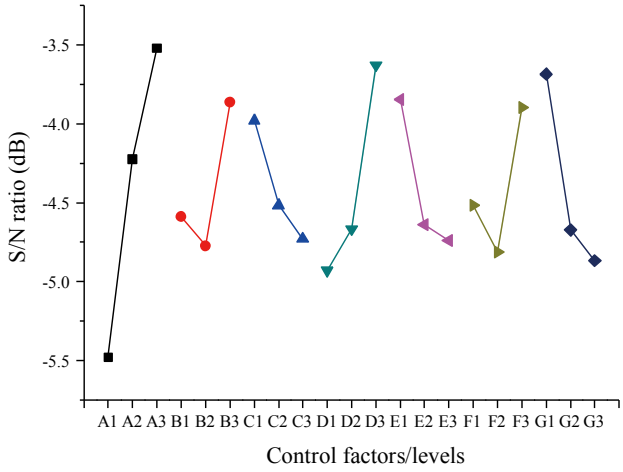


Fig. 4 The S/N ratios of the axial force for the 7 factors each at three different levels.

where X_i denotes the value of the ith factor (Table 1) and c_{i2} and c_{i1} are the coefficients for the quadratic and linear terms, respectively. The constant term for the relationship is summed up in c_0. The object functions that will be evaluated later include the anti-loosening torque ratio and the axial force ratio.

The validity of the regression function needs to be examined. Herein, a coefficient of determination R^2 was adopted. The larger the R^2 is, the more accurate the regression function becomes. The coefficient of determination was defined as the ratio of regression variance to total variance. It can be expressed as:

$$R^2 = \frac{SS_T}{SS_R} \tag{4}$$

where SS_T is the total sum of squares and SS_R is the regression sum of squares. The magnitude of R^2 lies between 0 and 1, i.e., $0 < R^2 < 1$. The closer the R^2 approaches 1, the better the regression function represents the physical relationship.

3. RESULTS AND DISCUSSION

3.1 Sensitivity and Analysis of Variance (ANOVA)

The 18 samples specified in Table 1 were manufactured and tested. The corresponding results were analyzed and presented in the following. Higher axial

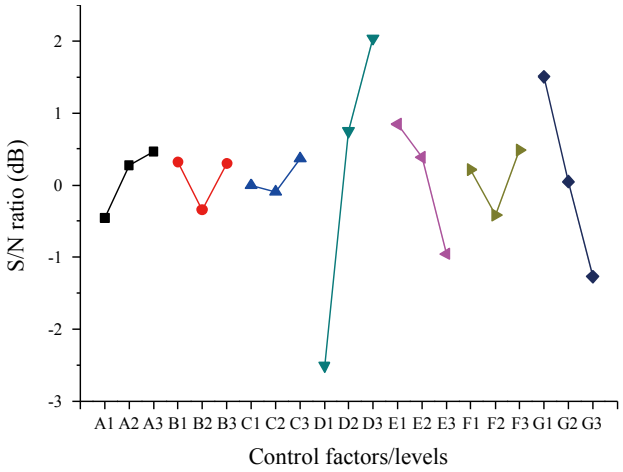


Fig. 5 The S/N ratios of the anti-loosening torque ratio for the 7 factors each at three different levels.

force ratio and anti-loosening torque ratio denote the better anti-loosening characteristics of the locknut. Figure 4 shows the S/N ratios of the axial force for the 7 factors each at three different levels. It is easy to find that the following combinations provide the design with the best axial force ratio: 14700 N axial pretension (A3), impact frequency of 20 Hz (B3), 1.2-mm displacement amplitude of the impact plate (C1), tightening torque of set screw of 7.65 N·m (D3), thread pitch of 1 mm (E1), concentrically ground collar surface (F3), and fit clearance of 0.03 mm (G1). Similarly shown in Fig. 5 is the S/N ratios of the anti-loosening torque ratio for the 7 factors each at three different levels. The design with 14700 N axial pretension (A3), set screw tightened to 7.65 N·m (D3), 1 mm thread pitch (E1), concentrically ground collar surface (F3) and 0.03-mm fit clearance (G1) had the highest anti-loosening torque.

The ANOVA analyses based on the measured axial force ratios and anti-loosening torque ratios from the samples were conducted and the results were presented in Tables 4 and 5, respectively. With respect to the axial force ratio, all the 7 factors had confidence larger than 99% and were significant control factors. On the other hand, for the anti-loosening torque ratio Table 5 shows only pretension axial force (A), tightening torque of set screw (D), thread pitch (E), machining process of the collar surface (F), and fit clearance (G) were significant factors with confidence greater than 99%. The frequency and displacement of the impact plate in the dynamic testing were insignificant factors. The anti-loosening torque of this class of locknut should derive from two possible mechanisms: the friction arisen from the axial force on thread of the locknut and the friction generated from the set screws on the thread of the locknut, respectively. The transverse impact from the driving plate, determined by the impact frequency and displacement amplitude, directly imposes a relative displacement between the locknut and the contact sleeve. This repetitive displacement could induce fretting wear on the interface between the locknut and contact sleeve. Subsequently, the axial force in the locknut assembly is influenced. However, the set screws in the locknut are

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Table 4 ANOVA for the axial force ratio.

Factor	SS	DOF	MS	F	Confidence	Significant
A	0.174	2	0.087	43.157	100.00%	Yes
B	0.038	2	0.019	9.398	99.95%	Yes
C	0.027	2	0.013	6.626	99.67%	Yes
D	0.085	2	0.042	21.020	100.00%	Yes
E	0.042	2	0.021	10.352	99.98%	Yes
F	0.038	2	0.019	9.426	99.95%	Yes
G	0.068	2	0.034	16.934	100.00%	Yes
Error	0.079	39	0.002	S = 0.0449		
Total	0.550	53	At least 99% confidence			

Table 5 ANOVA for the anti-loosening torque ratio.

Factor	SS	DOF	MS	F	Confidence	Significant
A	0.153	2	0.077	11.679	99.99%	Yes
B	0.032	2	0.016	2.902	93.32%	No
C	0.035	2	0.018	3.175	94.72%	No
D	2.399	2	1.199	217.472	100.00%	Yes
E	0.345	2	0.173	26.308	100.00%	Yes
F	0.132	2	0.066	10.070	99.97%	Yes
G	0.912	2	0.456	69.524	100.00%	Yes
Error	0.282	43	0.007	S = 0.0810		
Total	4.224	53	At least 99% confidence			

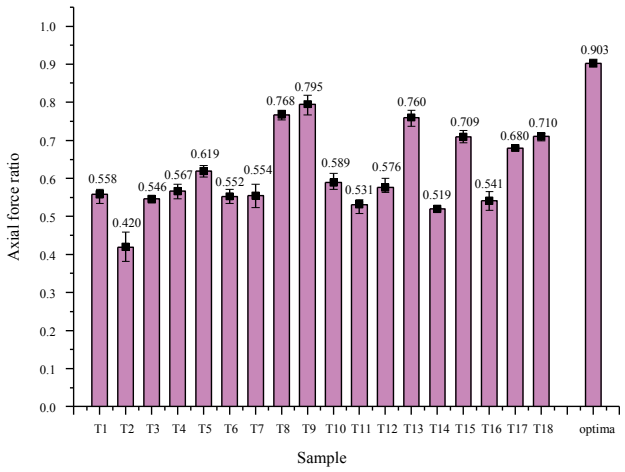


Fig. 6 The confirmation experiment on the design with optimal axial force ratio.

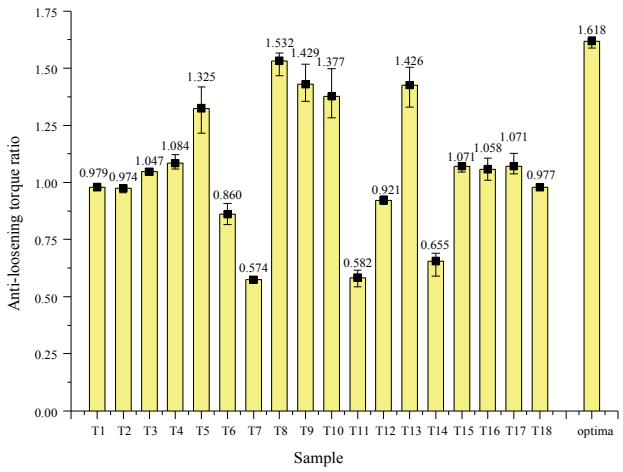


Fig. 7 The confirmation experiment on the design with optimal anti-loosening torque ratio.

subjected to less direct influence from the impact. Therefore, the anti-loosening torque controlled by the set screws can be less influenced than its axial force counterpart.

3.2 Confirmation Test

From the S/N ratios presented in Figs. 4 and 5, the optimal designs for the best axial force ratio and anti-loosening torque ratio were the ones with factor set (A3, B3, C1, D3, E1, F3, G1) and (A3, B1, C3, D3, E1, F3, G1), respectively. The confirmation experiments were conducted and the results are shown in Figs. 6 and 7. It is clearly seen in Figs. 6 and 7 that both confirmation experiments provided the best anti-loosening characteristics compared with the other 18 samples in the previous

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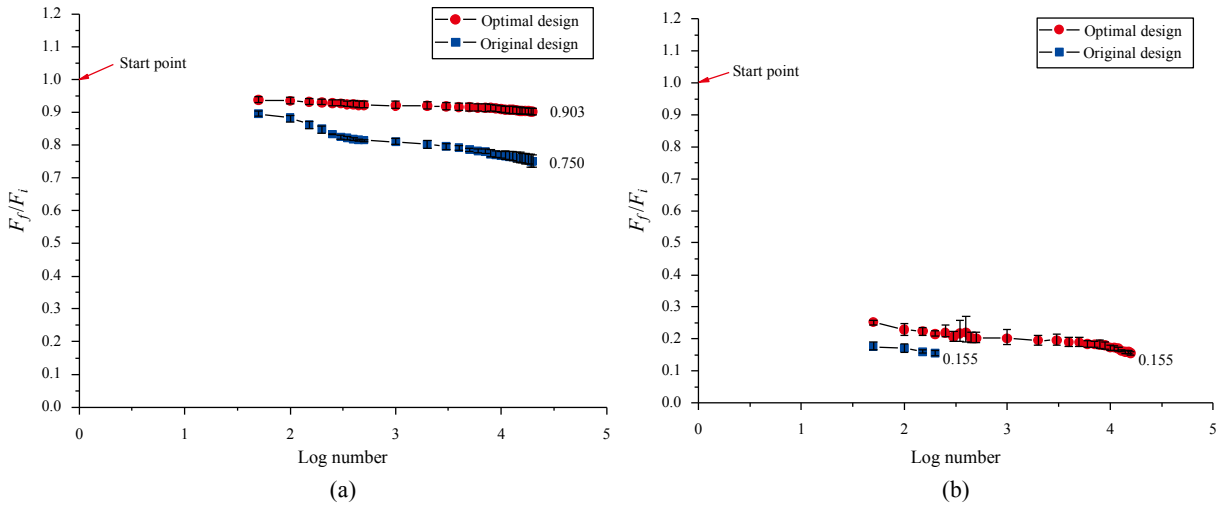


Fig. 8 The variations of measured axial force ratios for optimal and original designs under different testing conditions: (a) best scenario, (b) worst scenario.

Table 6 Regression coefficients for the two object functions.

Y	Axial force ratio	Anti-loosening torque ratio
c_{A1}	0.02659	0.03486
c_{A2}	-0.00064	-0.00112
c_{B1}	-0.08779	0.13563
c_{B2}	0.00287	0.00392
c_{C1}	-1.93917	-7.38750
c_{C2}	0.64167	2.94167
c_{D1}	-0.04266	0.10591
c_{D2}	0.00599	-0.00062
c_{E1}	-0.25967	0.35850
c_{E2}	0.06467	-0.18233
c_{F1}	-0.21778	0.05250
c_{F2}	0.13111	-0.41833
c_{G1}	-0.47421	-1.09498
c_{G2}	0.55284	0.78807
c_0	2.87909	6.19043

Table 7 The anti-loosening performance of the original and optimal designs of flank locking locknut.

Sample	Axial force ratio					Anti-loosening torque ratio				
	No. 1	No.2	No.3	Ave.	C.O.V.	No. 1	No.2	No.3	Ave.	C.O.V.
Original design	0.746	0.771	0.732	0.750	2.64%	1.319	1.462	1.377	1.386	5.19%
Optimal design	0.913	0.902	0.893	0.903	1.11%	1.588	1.638	1.629	1.618	1.66%
% of improvement				20.4					16.8	

experiments.

The collected axial force ratios and anti-loosening torque ratios for the 18 samples were used respectively in the multi-variable regression fit of function defined in Eq. (3) by SPSS software. The fitted coefficients for the two object functions are presented in Table 6. The calculated coefficients of determination of the regression functions for the axial force ratio and anti-loosening torque ratio were 88% and 97.3%, respectively. With the individual optimal design set for maximizing the axial force and anti-loosening torque, the predicted anti-loosening performances were 0.918 and 1.693, respec-

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tively. Compared with the experimental measurements of 0.903 and 1.618, the errors were 1.66% and 4.42%. Obviously, the regression fitted functions had very good reliability.

3.3 Improvement of Optimal Design Locknut over Existing Product

The flank-locking locknut of similar specifications in the market was the one with 1.5 mm thread pitch, fine turned collar surface and 0.2 mm fit clearance. Three samples for this original design and the optimal design obtained previously were fabricated and tested, respectively. The results are presented in Table 7. Both the improvements in axial force ratio and anti-loosening torque ratio of 20.4% and 16.8% for the optimal locknut demonstrated that the method proposed in this study was very effective.

The variation of axial force ratio over the test period for the optimal design is presented in Fig. 8(a). The axial force ratio response for the original design is also shown in the figure for comparison. As shown previously in Table 7, at the end of 20,000 times of impact loading, the axial force ratio reached 0.903 with little reduction from the beginning for the optimal design while quickly decrease to 0.750 for the original one. In order to further demonstrate the performance difference between the original and the optimal designs, the test factors for the worst scenario in axial force ratio were arranged: A1, B2, C3, D1, as indicated in Fig. 4. Since the loosening of the fastener assembly could cause the disintegration of the test setup, the equipment was set to automatic stop for safety concern whenever the measured axial force ratio had lowered to 0.155. Figure 8(b) apparently shows the testing stopped for both designs after certain period of time elapsed. However, the optimal design endured 16,000 times of impact which was far more superior to the 200 times of its original design counterpart.

4. CONCLUSIONS

The Taguchi method was employed in this study to explore the anti-loosening characteristics of a flank-locking locknut. By selecting 7 factors and 3 levels for each one, 18 samples were manufactured and experimentally tested under periodic impact loading. The significant factors controlling the axial force ratio and anti-loosening torque ratio were determined. For controlling the anti-loosening torque performance, the axial pretension force, thread pitch, machining process for the collar surface, tightening torque of the set screw and fit clearance of the nut were all significant factors to be considered. The optimal design for maximizing the axial force ratio was found to be the one with: 14700 N pretension, 20 Hz impact frequency, 1.2 mm impact displacement amplitude, 7.65 N·m set screw tightening torque, 1 mm thread pitch, concentrically ground collar surface, and 0.03 mm fit clearance of nut. The performance of this optimal design was validated through a confirmation experiment which demonstrated a maximized axial force ratio of 0.903. A 20.4% improvement in the axial force ratio was obtained comparing with a product in the market having similar specifications. The experimental findings confirm the user experience: the higher pretension and tightening torque and the finer pitch, surface roughness and fit will yield a better locknut. Finally, a regression function based on the results of the 18 samples for the axial force ratio performance was proposed. The reliability of this regression function was validated with the optimal design and a prediction of 0.918 was obtained for the axial force ratio. This result was within 2% of difference with the experimental measurement. Therefore, the regression function can facilitate the designer to explore the performance of the different designs.

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