Development of analytical prediction method for pulley bolt-loosening

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Abstract: Many auxiliary parts (e.g. the water pump, the oil pump, the alternator, and etc) in an engine are driven by the crankshaft. For this, a pulley is assembled to the crankshaft by a bolt. A bolt-loosening of the pulley can cause noise and vibration and bring engine breakdown in severe case. A finite element analysis procedure and a rig test were developed to predict a bolt-loosening of the pulley. The FE analysis results agree with the rig test results and verified with the real engine test. The parameters making worse the bolt-loosening are investigated. They are the torsional and lateral vibration of the crankshaft, the belt tension, the belt torque variation and the pulley inertia. Authors thought this procedure developed here can be applied to solve a bolt-loosening in other system.

Keywords: Engine, Crankshaft, Pulley bolt, Bolt-loosening, FEA.

1. Introduction

For the engine operation, the crankshaft runs the auxiliary parts such as the water pump, the oil pump, the alternator, the valve-train, and etc. These parts are run by the crank pulley with a belt or a chain. By a bolt the pulley is fastened to the crankshaft front as shown in Fig. 1. Since the combustion pressure in the cylinder and inertial force due to the moving elements are not continuous but periodic, torsional and lateral vibrations are excited to the crankshaft. These vibrations turn into the periodic shear load and bending moment to the pulley clamped system and the pulley bolt is loosened when the bolt force is insufficient. Sometimes it causes the failure of the crank-train system.

The known methods to set the initial force of the pulley bolt are based on the theoretical approach. The methods do not consider the external forces in detail therefore people have doubts whether they give the proper initial level of the bolt force.

This study developed a FEA (finite element analysis) procedure to predict the bolt-loosening possibility of the pulley bolt via rig tests. The effect of the design parameters of the pulley system is analyzed as well and the reliability of the pulley system is checked under the actual engine condition.

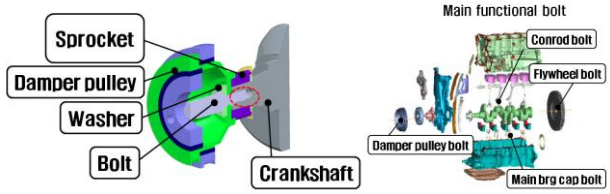
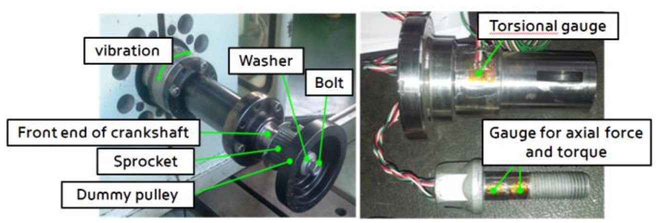


Figure 1. Crank pulley system

2. Rig test

Figure 2 shows the configuration of the rig tests to reproduce bolt-loosening. Since the important is the frictions between the parts in order to simulate the bolt-loosening, the actual productions have to be used. A front end piece of crankshaft, a dummy pulley, a sprocket, a washer, and a bolt were assembled. The dummy pulley is designed with a large inertia for an ease bolt-loosening. After fastened, torsional vibration is applied to the crankshaft. As the level of the external applied angle is increased, the axial bolt force, the torque of the bolt, and the torque of the front end of the crankshaft are measured to monitor the bolt-loosening. The test was carried out with various tightening torque levels and the results are summarized in Table 1.



(a) setup (b) gauge to monitor force and torque

Figure 2. Rig test (a) setup (b) gauge to monitor force and torque

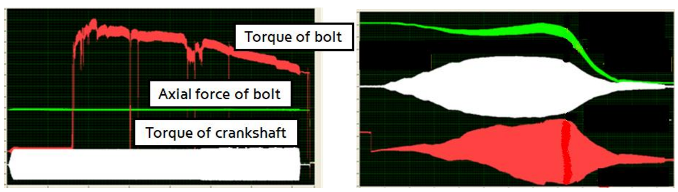
Clamping torque(kgf.m)	Angle of vibration (deg)		
	0.2	0.3	0.35
4	No bolt-loosening /bolt-loosening	No bolt-loosening	bolt-loosening
5	No bolt-loosening	bolt-loosening	bolt-loosening
6	No bolt-loosening	No bolt-loosening /bolt-loosening	No bolt-loosening
8	No bolt-loosening	No bolt-loosening	-

Table 1. Bolt-loosening results by rig test

Without a bolt-loosening, there is no change in the bolt force (Fig. 3a). Even the torque of the bolt is decreased the torque amplitude of the front end of the crankshaft is stable. However if there is a bolt-loosening, the monitored signals show different trends. The bolt-loosening is easily seen in the graph; the sudden drop of the bolt force.

The torque amplitude of the bolt continuously increases before the bolt-loosening. However the torque average of the bolt remains the same level. Whereas the average torque of the front end of crankshaft keeps a certain value as same as the bolt torque, the amplitude increases in the beginning and becomes stable before the bolt-loosening. When the bolt-loosening begins, the both amplitudes start to decrease.

As shown in Table 1, the bolt-loosening is easily occurred for larger external applied angle. And the higher value of external angle is needed for the higher initial tightening bolt force. These results coincide with the common sense. There are two cases which conflict the common sense. It is believed that it comes from the experimental scatter due to the friction condition.



(a) no bolt-loosening (b) bolt-loosening

Figure 3. Rig test signal (a) no bolt-loosening (b) bolt-loosening

3. Finite element analysis

3.1 Model configuration

The finite element model for the analysis is displayed in Figure 4. In order to simulate the bolt-loosening, the female thread in the crankshaft and the male thread in the bolt are modeled in actual 3-dimensional shape as same as the rig test. ABAQUS is used for the analysis.

There is a pin connecting the pulley and the sprocket, so the pulley and the sprocket rotate together. For the simple model, the pin is omitted in the finite element model and the face between the pulley and the sprocket is set as fully fixed condition. The finite sliding option is applied to other contact surfaces. A bolt-loosening greatly depends on the occurrence of the slip at the interface. Hence the most importance in the bolt-loosening analysis is the friction around the bolt. The coefficient of the static friction (μ_s) and the kinetic friction (μ_k) at the bolt thread were measured respectively for the accuracy of the analysis. No details about friction coefficients and mechanical properties of the parts used in the analysis.

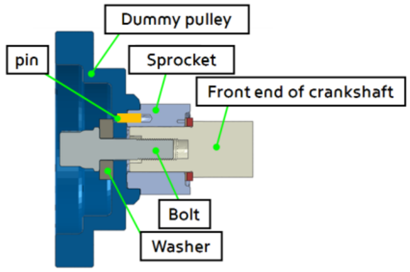
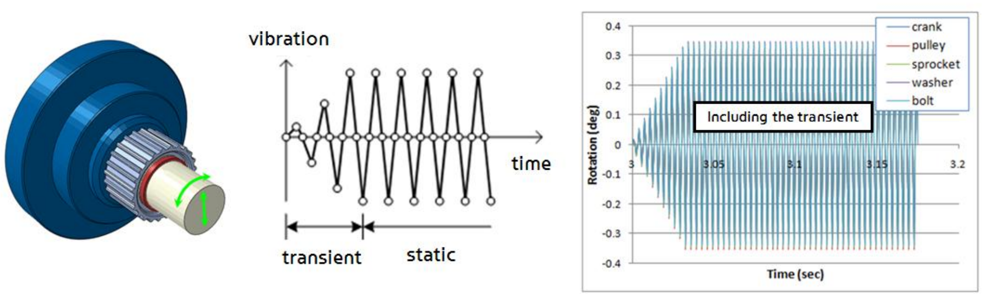


Figure 4. FE model

The FE analysis for the bolt-loosening follows the actual process; a tightening and a bolt-loosening. To tighten the bolt, a rotation is applied to the bolt with the design torque. Since the effect of inertia during the rotation is negligible, the inertia is not considered here. The kinetic friction coefficient is used for the tightening analysis. In order to find out the bolt-loosening, the pretension section of ABAQUS option is fixed at the beginning of the analysis and the bolt force is monitored during the whole analysis.

Since the crankshaft inertia force due to the external excitation is the greatest parameter on the bolt-loosening the bolt-loosening analysis was performed with the dynamic analysis. Once the bolt tightened, the interfaces are fixed. Therefore the static friction coefficient is used at the thread areas in the loosening analysis. For the external excitation, the amplitude is increased gradually to the desire value to prevent the sudden load of the inertia which may bring the unwanted slip between the crank and sprocket. The amplitude of excitation to the time is schematically shown in Fig. 5a which shows a transient in the beginning. Figure 5b is the variation of the rotation angle of each part due to the torsional vibration, which has the same trends with the excitation so it proves indirectly the reliability of the analysis.

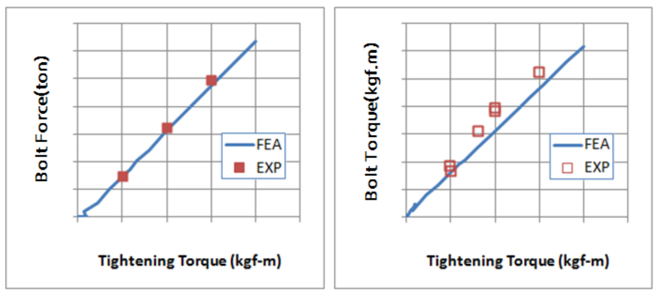


(a) Torsional excitation amplitude (b) Rotations of parts due to excitation

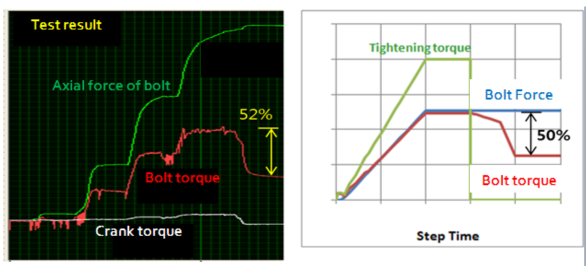
Figure 5. (a) Torsional vibration excitation and (b) Rotation results of parts due to excitation

3.2 Verification of FE analysis

The results of analysis were compared with those of the rig test for the reliability of the FEA procedure developed here. Figure 6a and 6b present respectively the changes in axial force of bolt and torque of the bolt shank to the tightening torques in the tightening process. The axial forces obtained by FE analysis are almost identical to the test results. In case of the torque of the bolt the FE results agree with the experimental data well even though the analysis results are slightly lower. In the real field, there is a torque drop of the bolt when the bolt-tightening is ended and the wrench on the bolt is removed. Figure 6c and 6d show that the FEA results present this phenomenon as same as the real. The torque drop in the rig test and FE analysis are respectively 52% and 50%, so that the rig test and FE results showed a good relation.



(a) Bolt force comparison (b) Bolt torque comparison

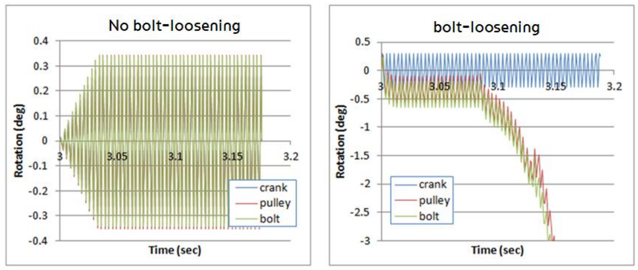


(c) Bolt force drop in rig test (d) Bolt force drop in analysis

Figure 6. Comparison of FE results and rig test (a) Bolt force comparison (b) Bolt torque comparison (c) Bolt force drop in rig test (d) Bolt force drop in analysis

3.3 Prediction of the bolt-loosening

The bolt-loosening is definitely based on the slip at the interface of the parts. If the bolt is not loosened, change of the rotation angle of all parts is the same as vibration of the crankshaft. The slip causes the difference of the rotation angle between the part and the crankshaft. Figure 7 shows the changes of rotation angle to the time obtained by the FE analysis. There is no relative rotation to the crankshaft in Fig. 7a, which means no bolt-loosening. Fig. 7b presents the rotation of the pulley and the bolt is enlarged, which means the bolt-loosening. Since the crankshaft is excited, the reference is the crankshaft and the rotation of the crankshaft remains constant.



(a) No bolt-loosening **(b) Bolt-loosening**

Figure 7. The changes of rotation angle to the time

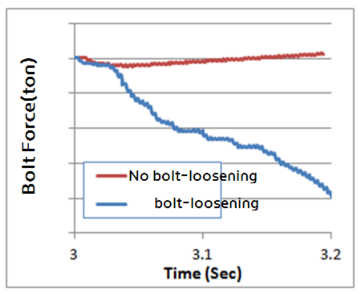


Figure 8. The bolt force for the cases of with or without bolt-loosening

The bolt-loosening surely brings the reduction of the bolt force. Therefore when the bolt force decreases we notice the bolt-loosening. Figure 8 shows the bolt force for the cases of with or without bolt-loosening. It is easily seen that there is significant reduction in the bolt force with the bolt-loosening. However the change in the bolt force is negligible without bolt-loosening. Both of the analysis and experiment results are plotted at once in Fig. 9. The black line is the border line for the bolt-loosening. The safe region for the bolt-loosening is below the black line. Even though there two exceptional cases from the test as already listed in Table 1, the border line well defines the guideline in the bolt force and the external torque amplitude to the bolt-loosening.

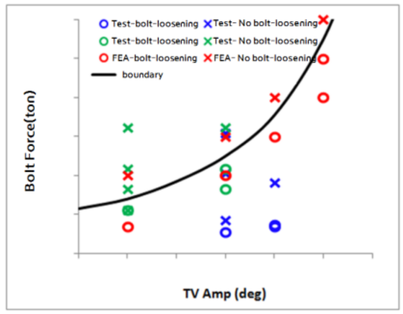
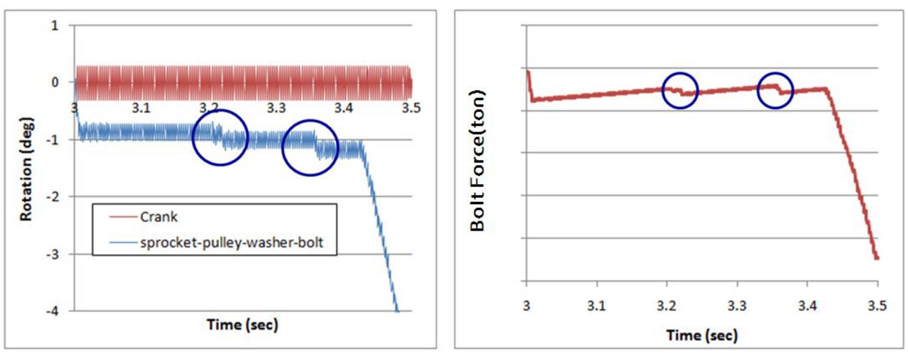


Figure 9. Border line of bolt-loosening

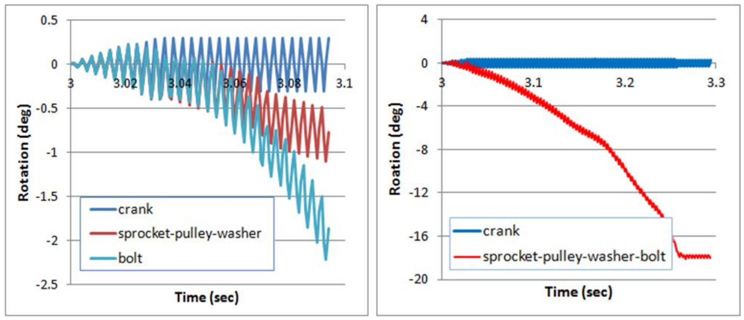
When the conditions of the bolt force and the external excitation is just above the border line, the progress of the bolt-loosening is very slow and the detection of the bolt-loosening is quite difficult. In this case, it is better to use the rotating angle of parts instead of the bolt force. Figure 10a shows the changes in the rotation angle of parts and the bolt force in case of the slow bolt-loosening. The rotation angle of the sprocket does not change for a certain time but the rotation angle is slightly and instantly stepped down around 3.2 second. And another slight step-down is around 3.35 second. However it is not easy to notice this behavior with the bolt force as shown in Fig. 10b. After the time of 3.4 second, the changes of the rotation angle and the bolt force increase rapidly.



(a) Rotation **(b) Bolt force**

Figure 10. Detection of bolt-loosening (a) rotation (b) bolt force

When the bolt-loosening is happened, two kinds of the rotation behavior are observed in the bolt-loosening analysis. In Fig. 11a three parts (the sprocket, the pulley, and the washer) moved together and became larger as the time goes. But the bolt gave more rotations than them. Meanwhile, all the parts except the crankshaft moved together in Fig. 11b and the speed of the rotation increase is much faster than that of Fig. 11a. The behavior in Fig. 11b is the same with the rig test. This result informs that the slip between the crank and sprocket always occurs when the bolt is loosened.



(a) Slow bolt-loosening (b) Fast bolt-loosening

Figure 11. Rotation behavior for two bolt-loosening cases (a) slow bolt-loosening (b) fast bolt-loosening

4. Effect of external forces and design parameters

4.1 Vibration of crankshaft

The effects of the external forces and the design parameters on the bolt-loosening are discussed here. The first is the effect of the external excitations of the crankshaft. The torsional vibration amplitude (TVA) of crankshaft and the lateral vibration amplitude (LVA) are respectively investigated with the range of 0.2 ~ 0.4 degree and 0.0 ~ 0.1mm. The results from FE analysis were summarized in Table 2. The white columns of the table mean the cases without LVA. The axial force of bolt loosening increases as the torsional amplitude increase. When the bolt is tightened with a higher initial value, higher TVA is required for the bolt-loosening. If no bolt-loosening is occurred under the external excitations (TVA + LVA), the increase of TVA or LVA brings a bolt-loosening. For example, there is no bolt-loosening for the initial bolt force of 4 ton under 0.3 degree of TVA excitation. If the 0.1 mm of LVA is added or TVA is increased as 0.35 degree, the bolt-loosening will happen. It is concluded that higher amplitude of torsional and/or lateral vibration of crankshaft increases the possibility of bolt loosening.

Torsional vibration (no bolt-loosening NG, bolt-loosening OK)		TVA(deg)+LVA(mm)						
		0.2+0.0	0.3+0.0	0.3+0.1	0.35+0.0	0.35+0.1	0.4+0.0	0.4+0.1
Bolt tension (ton)	1.7	OK						
	3	NG	OK					
	4		NG	OK	OK			
	5				NG	OK	OK	
	6						OK	
	7						NG	OK

Table 2. Effect of vibration of crankshaft

4.2 Belt tension

As explained in the introduction, the auxiliary parts are linked with the pulley via a belt or a chain. A belt tension applies forces to the pulley and the sprocket. The effect of the belt tension is examined here. Figure 11 shows the rotation angle of the sprocket for the belt tension of 0.15 kN and 0.2 kN. In here, the torsional amplitude, lateral amplitude, and the bolt force are fixed. There is no bolt-loosening for the belt tension of 0.15kN while the rotation angles of parts were made for the belt tension of 0.2 kN. It is figured out that the possibility of bolt loosening increases as the belt tension increases.

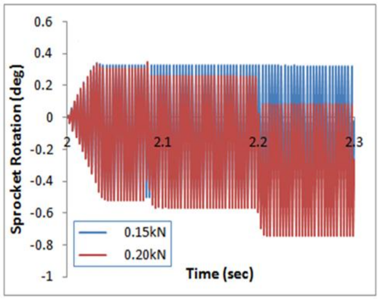


Figure 12. Effect of belt tension

4.3 Inertia of the pulley

One of possible parameter in the bolt-loosening is the inertia of the pulley. To consider the inertia effect, the density of the pulley is changed without change in the shape of the pulley. As seen in Fig. 13, when the density of the pulley is decreased the bolt-loosening is disappeared. The bolt force is 3 ton and the torsional amplitude of the crankshaft is 0.25 degree. The pulley inertia and the possibility of bolt loosening have a linear relationship.

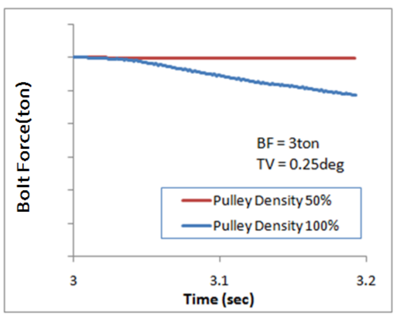
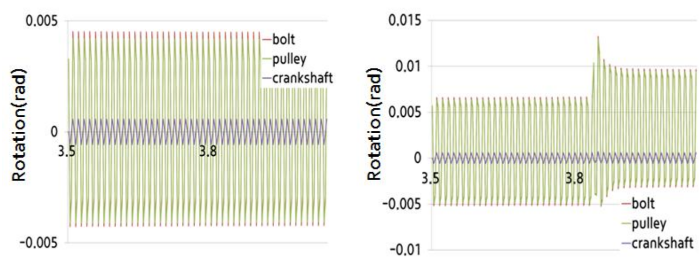


Figure 13. Effect of pulley inertia

5. Application to real engine

The method developed in this study is applied to a real engine to verify its reliability. The analysis follows the same procedure explained in the previous sections. The values of the tightening and the excitation are given as same as the real engine condition. When the bolt is tightened with the regular condition, there is no bolt-loosening (Fig. 15a). However if the tightening bolt force is less than the regular value, a bolt-loosening begins (Fig. 15b). Less the bolt force accelerates the bolt-loosening (Fig. 16).

A real engine with the bolt force under the regular value is tested and the bolt-loosening is observed as same as expected by the FE analysis. The procedure built here is verified by the real engine test.



(a) Tightened regular bolt force **(b) Tightened less regular bolt force**

Figure 15. Rotations in real engine condition (a) tightened regular bolt force (b) tightened less regular bolt force.

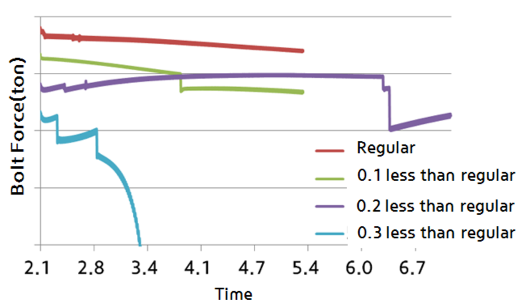


Figure 16. Bolt force in real engine condition with various tightened bolt force condition

6. Conclusion

In this study, developed the rig test method to reproduce the bolt-loosening and the FE analysis procedure to predict the bolt-loosening. The FE analysis results agree with the rig test results and verified with the real engine test.

The effects of some parameters and external forces affecting the bolt-loosening are investigated as well. As the results, the torsional and lateral vibration of the crankshaft, the belt tension, the belt torque variation due to the variation of the belt tension, and the pulley inertia are found. All the factors mentioned above increase the possibility for bolt-loosening.

Authors expect this procedure developed here can be applied to other system related with the bolt-loosening.

7. References

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