IMECE2012-86415

THE ABSOLUTE EVALUATION AND LOOSENING LIFE PREDICTION METHOD ON SELF-LOOSENING OF BOLTED JOINTS DURING ACTUAL MACHINE OPERATION

Soichi Hareyama
Guest Professor
Tokyo Metropolitan University
Hachioji-City, Tokyo, Japan
hare-lab@ivy.ocn.ne.jp

Ken-ichi Manabe
Professor, Department of Mechanical
Engineering,
Tokyo Metropolitan University
Hachioji-City, Tokyo, Japan
manabe@tmu.ac.jp

Makoto Nakashima
Chief, Technical Research Center,
TCM Corporation
Oumihachiman-City, Shiga, Japan
m.nakashima.if@tcm.co.jp

ABSTRACT

This paper presents a method for estimating the absolute lock effect in bolted joints during actual machine operation.

The absolute evaluation on self-loosening is indispensable for the prediction of the life of locking devices (parts)/method at actual machine operation. The loosening phenomenon of bolted joint can be viewed as the decrease tendency of the initial axial tension or residual axial tension. According to the author's previous report, there is a good linear relation on logarithmic coordinates (log-log paper) between the decrease of axial tension (measured tension/initial axial tension) and number of operations (or working time or mileage) since last tightening.

Based on this relation, and observation of loosening in the early stages of product development, we estimate the rate of axial tension decrease (degree of self-loosening) accurately after prolonged operation since tightening by measuring the initial axial tension behavior by using the proposed regression formula. The trial calculation of the residual axial tension after prolonged operation is made using the industrial vehicle (stacking capacity 16-ton large-sized forklift-truck) at customer's site by loosening measurement. According to the estimation using only a few day's data, it is presumed that initial axial tension is kept 55% or more in case of anaerobic adhesive tightening and almost 30% in case of lubrication tightening after ten years.

In the working load type loosening, authors propose the L-N diagram (Loosening Life - Numbers of Cycles to Loosening N Diagram) for loosening life estimation like the S-N diagram for fatigue life estimation. Using the loosening frequency diagram and L-N diagram, the degree of loosening damage for every axial tension's residual ratio is figured out to analyze the loosening life of the locking device/method by Miner's rule and cumulative loosening damage models.

INTRODUCTION

A gadget, a machine, and a spacecraft may not even exist without a screw/bolt, either. Although a screw/bolt is the machine part made by the simple principle of a wedge and a spiral and it is a machine element used for more than 2000 years, troubles such as poor bolting, self-loosening, and insufficient strength occur even today.

It seems that it is due to its usage as a fastening object shown in table 1, and its characteristics.

The optimum tightening condition of bolted joint used in machines is defined as the state in which it is tightened with high axial tension sufficient to be free from breakage and loosening by any external force during machine operation [1].

In this report, the absolute estimation method of self-loosening for the locking device of bolted joint is proposed. Our basic question is "Until how many tens of thousands of the operations does the locking device (method) maintains the axial tension (clamping force) from becoming loose?" for example.

The absolute evaluation on self-loosening is indispensable for the prediction of the life for locking devices (parts)/method at actual machine operation. With regard to self-loosening, the relative evaluation of parts/method is performed by using a Junker's style loosening test equipment.

Table 1: Basic problems in bolted joints

item
(1) It is always used at high stress. It is subjected to vibration and repeated external force.
(2) Although high initial axial tension is needed, there is no simple tool. Therefore, calibrated wrench method must be used in general.
(3) There are many kinds of bolts/screws (coarse / fine screw thread, strength grade classification, etc.).
(4) Breakage of screw threads and damage through defomation (cross-sectional reduction) may be caused by tightening work.
(5) High stress concentration areas exist in the underhead fillet part and a threaded portion, etc.
(6) Fatigue breakage, hydrogen embrittlement, etc. occur during machine operation.
(7) Self-loosening easily occurs due to the spiral shape and is influenced by depression of bearing surface.
(8) Many bolted joints are used in one product.

There are many literatures or views and the elucidation of the self-loosening mechanism, etc. Especially, the research of Junker gives many suggestion on the mechanism and the laboratory loosening test method[4,5]. Many reports[6]～[10] describe the evaluation of a loosening test method and some locking devices, such as reports by Clark[6] and Hongo [7].

JFRI[8] obtained cooperation of many universities and a company, and carried out many loosening examinations.

Yamamoto[9] is introducing Junker's estimation method. It referred for that Junker uses vibration power for the evaluation index, its evaluation result, etc. in it.

In the latest researches, Shoji and et al[10] clarified the loosening mechanism at horizontal load, and Vinogradov and et al[11] clarified the loosening mechanism at high frequency load by numerical analysis. Daadbin and et al[12] clarified the loosening mechanism under vibration by logical model, and considered the influence on loosening from the perspective of shock durable period, coefficient of friction and lead angle. Hess and et al[13] modeled single bolted joint and presented displacement of each part under oscillating load as logical formula; also made loosening evaluation using the testing machine. Zadoks and et al[14] developed the mathematical model of dynamic loosening of the bolted joint as the 1st step.

Izumi and et al[15] analyzed the loosening mechanism by shear load using three-dimensional finite element method. Nishimura and et al[16] studied the relation between slide displacement and loosening. Hongo[17] classified the loosening mechanism largely into two: a) generated by relative rotation between bolt and nut, and b) generated without any relative rotation between bolt and nut.

The analyses of these loosening mechanisms give many suggestions to the elucidation of a loosening phenomenon. However, the solution has not been given yet from the perspective of absolute evaluation of locking devices.

There are reports[18]～[21] on the result of evaluation of locking effect using the loosening testing machine.

Yamamoto[18] is introducing Junker's evaluation result in detail. Kasei[19] summarizes the research trend of self-loosenin and is summarizing the quality assessment of locking parts/method etc. Kumakura and et al[20] evaluated the locking effect of joint with gasket under the load in axis direction with different nut height. Sase and et al[21] evaluated the locking performance of various kinds of locking parts.

However, these estimation methods are just the evaluations on performance of locking devices in laboratory test. They enable qualitative evaluation as well as relative comparison on loosening-preventive performance of locking parts (devices) quantitatively. Yet, they cannot perform absolute evaluation on whether the bolted joint makes specified performance and maintains its initial performance after lapse of certain period of time during actual machine operation. Zhao and et al[22] use the logarithm equation to the problem of loosening like this paper .Although researches on this kind of absolute estimation method is not found other than the paper of authors[2,3].

This research does not deal with the principle of loosening of a screw (bolted joint) or the mechanism for cause of loosening. It deals "Until when does the locking devices (parts)/method maintain the initial locking performance?"

Self-loosening phenomenon can be classified into the depression type (static) and the working load type loosening (dynamic). In development phase of actual machine, data for both types of loosening may be collected simultaneously or separately at different times. The method of presuming the grade and loosening life data collected separately at different times is proposed. Synthetic loosening is figured out as the sum of depression type and working load type loosening.

In the working load type loosening, authors propose the L-N diagram (Loosening Life - Numbers of Cycles to Loosening N Diagram) for loosening life estimation like the S-N diagram for fatigue life estimation. Using the loosening frequency diagram and L-N diagram, the degree of loosening damage for every axial tension's residual ratio is figured out to analyze the loosening life of the locking device/method by Miner's rule and cumulative loosening damage models.

We discuss the possibility of association between relative evaluation of loosening tendency and absolute evaluation of the laboratory loosening test and actual machine operation.

OBSERVATION OF LOOSENING PHENOMENON
(Axial Tension Decrease Tendency and Introduction of Regression)

The loosening tendency of the bolted joint used in machine is measured in the actual operation site. Figure 1 shows the industrial vehicle (stacking capacity 16-ton large-sized forklift-truck) used in loosening measurement at customer's site. Figure 2 shows the setup state of a test bolt and its specifications.

There are cylinder mount bolts of the forklift-truck for steering and receives the repeated external force in the direction of bolt axis at the time of operation. Test bolts are steering cylinder mount bolts of the forklift rear axle part, as shown in the schematic diagram in fig. 2. Since the knock (dowel) pin is used, the pin receives the external transverse force. The axial load and the bending moment mainly act on the test bolts. It is important to investigate the loosening phenomenon for every load situation. Those subjects are made into the theme of research of the following stage. This paper observes the axial-tension reduction tendency (loosening behavior) of the test bolts first, and arranges it.

The test bolts are tightened with predetermined bolting torque shown in table 2. The table also shows tightening condition and initial axial tension relatively.

Axial tension decrease tendency of test bolts is measured from the initial stage of bolting work in the factory to the transportation to a customer's site. Figure 3 shows the phenomenon in early stages of self-loosening. As an early phenomenon, the axial tension decrease tendency is measured from about 30 minutes after test bolt bolting for 13 hours. Although relatively large axial tension decrease of about several percent of initial axial tension is observed in early stages of bolting, it is a gradual decrease tendency after that. After bolting, the truckload work of a test forklift is done and the oscillatory waveform is observed about 1 hour later. The oscillatory waveform while being conveyed on the track is observed.

Fig. 1: Test forklift-truck under actual operation at customer's site

Figure 4 shows these waveforms plotted for about 13 hours on log-log paper (logarithmic coordinates). Center value is taken at plotting under a truckload, conveyance, and shipping-and-discharging work has taken the center value.
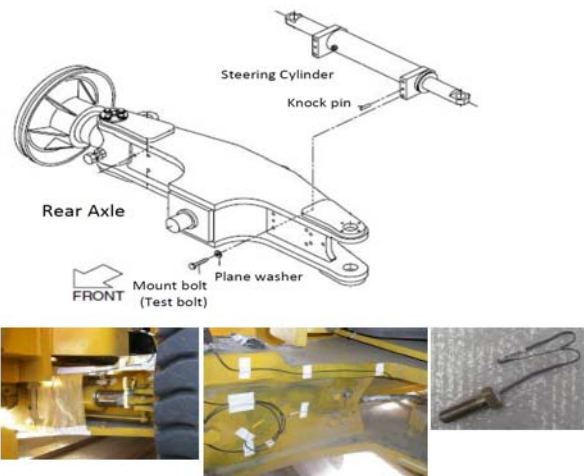
Fig. 2: Test fork-lift axle and test bolt specification

Table 2: Tightening condition

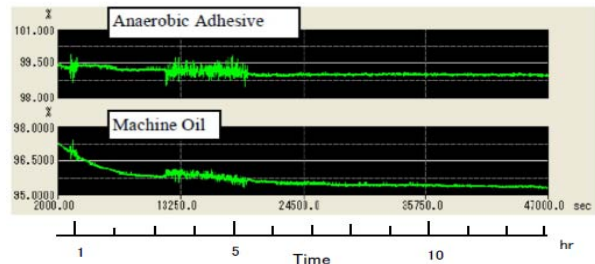| Tightening method	Calibrated wrench method	
Tightening condition (lubrication)	Machine oil	Anaerobic adhesive (LOCTITE #262)
Tightening torque (N·m)	233	268
Initial axial tension (kN)	63.6	55.2

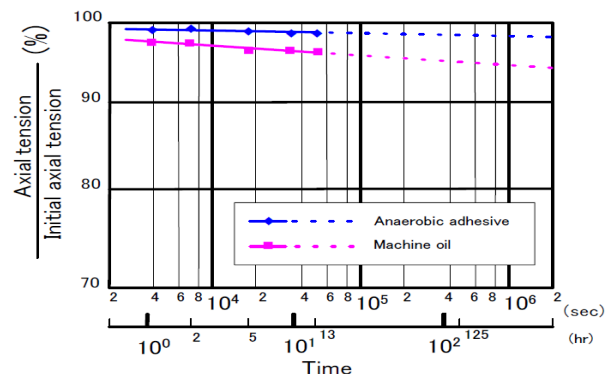**Fig. 3:** Depression type loosening (Linear coordinates)

Fig.4: Depression type loosening (Logarithmic coordinates)

This data does not almost have the actual work of a forklift, and it can be concluded that most has caught the depression type loosening phenomenon. The observation result also shows the good alignment tendency which may be sufficient in logarithmic coordinates same as our previous reports [2] and [3].

The diagram in fig. 4 can be expressed by the following regression formula.

$\log r = a + b \times \log h$ ----- (1)

Here, h: Operation Interval (hour)

r : (Measured Axial Tension)/(Initial Axial Tension)

a, b : Constants

If this regression formula is applied to the result of fig. 4, the regression of a formula (2) will be obtained by machining oil lubrication tightening, and the regression of a formula (3) will be obtained by anaerobic adhesive tightening.

$1000 \times \log r = -13.7 - 8.13 \times \log h$ ······(2)

$1000 \times \log r = -3.93 - 1.58 \times \log h$ ······(3)

These 2 types are the regression of depression type loosening.

ANALYSIS OF SELF-LOOSENING PHENOMENON

Detailed analysis of the observation result of the loosening phenomenon (initial axial tension decrease tendency) in a customer site is measured using the large-sized forklift truck shown in fig. 1.

LOOSENING LIFE PRESUMPTION BY AXIAL TENSSION WAVEFORM OBSERVATION AND ANALYSIS USING REGRESSION FORMULA

The loosening phenomenon at the actual machine operation in the customer's site is continuously observed for about over one month, including the state such as self-running between customer's site and another site. The waveforms of fig.5 show the continuous decrease tendency (loosening) of the bolt axial tension at the time of a series of above-mentioned operation. The figure is a part of result (for four days) measured with the linear scale for a long period of time at customer's site. The customer's operator used the test forklift-truck freely, and these waveforms are measured in free operation. Operating conditions are not particularly requested to the operator. Therefore, when performing axial tension measurement, influences of many factors such as inclination of the road surface and the stop posture of the test machine are included. Loosening Observation data are measured continuously since initial tightening and the lapsed time is also shown in each graph. Figure 5 shows the data of observation of the morning and afternoon for the loosening phenomenon of the bolt axial tension continuously from bolt tightening through the end of actual machine operation at customer's sites. The waveform of the upper row is a working waveform of the test bolt axial tension tightened by anaerobic adhesive and lower is lubrication tightening. The vertical axis shows initial axial tension as 100% like fig.3 on linear coordinates. Both waveforms show all the data at the time of the actual machine operation of a test forklift, and the total hours worked for four days are about 25 hours. The data of stopping in the nighttime is omitted. Bolt axial tension makes repeated fluctuation to increase and decrease side by external force. In the observation of these waveforms with a lubrication tightening bolt, shocking loosening (axial tension decrease) will be seen in some places like an example shown by the enclosure line of the ellipse. Figure 5 captures the state in which bolt axial tension drastically fluctuates. In particular, a working waveform receives an impact load, and axial tension is changing momentarily. Bolt nut is considered to rotate momentarily in the direction it loosens relatively according to impact load.
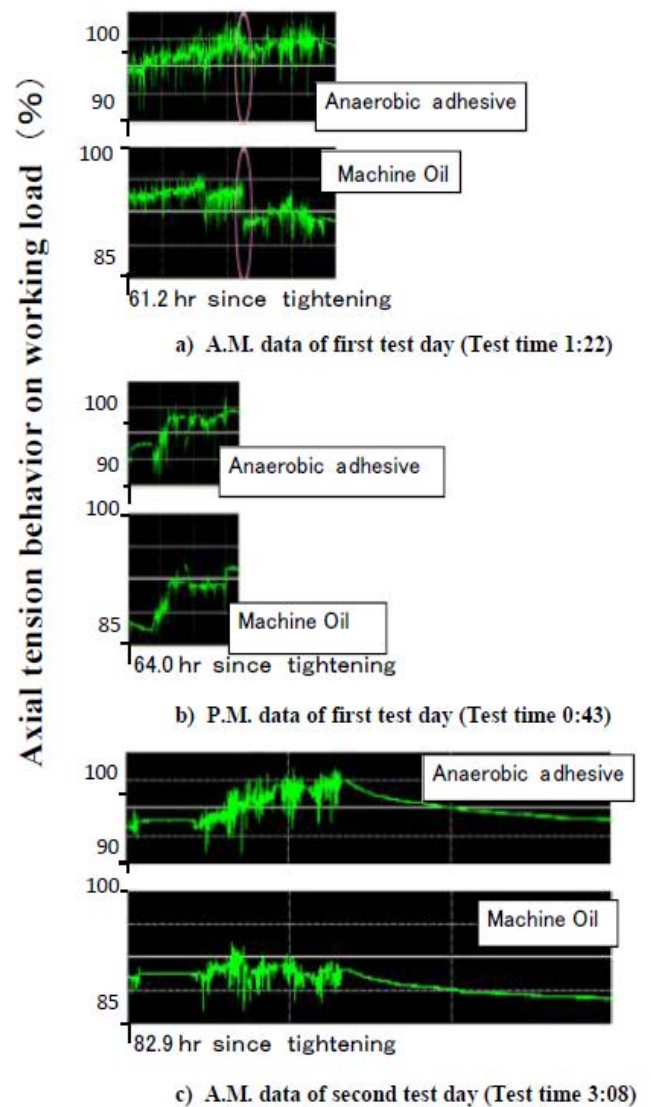

Fig. 5-(1): Working load type loosening (Linear coordinates) (Axial tension behavior in customer since tightening)
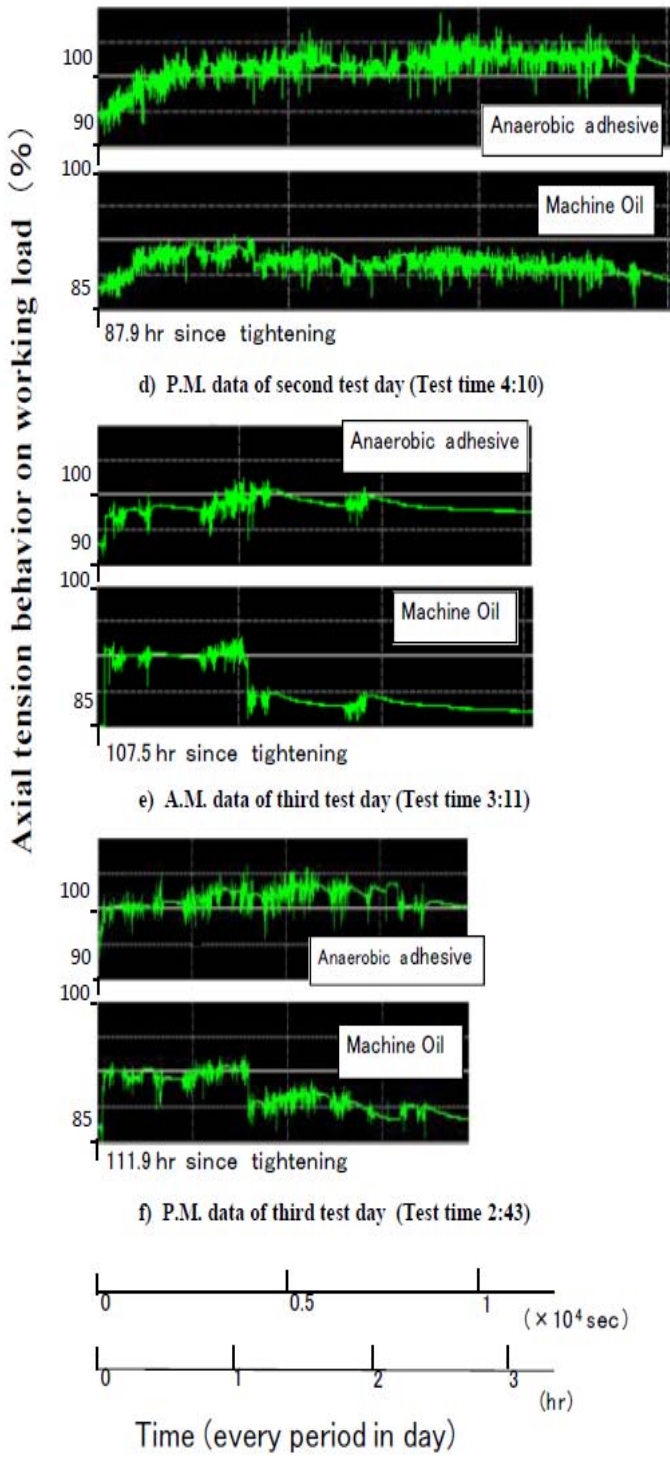
d) P.M. data of second test day (Test time 4:10)

e) A.M. data of third test day (Test time 3:11)

f) P.M. data of third test day (Test time 2:43)

Fig. 5-(2): Working load type loosening (Linear coordinates)
(Axial tension behavior in customer since tightening)

g) A.M. data of fourth test day (Test time 3:44)
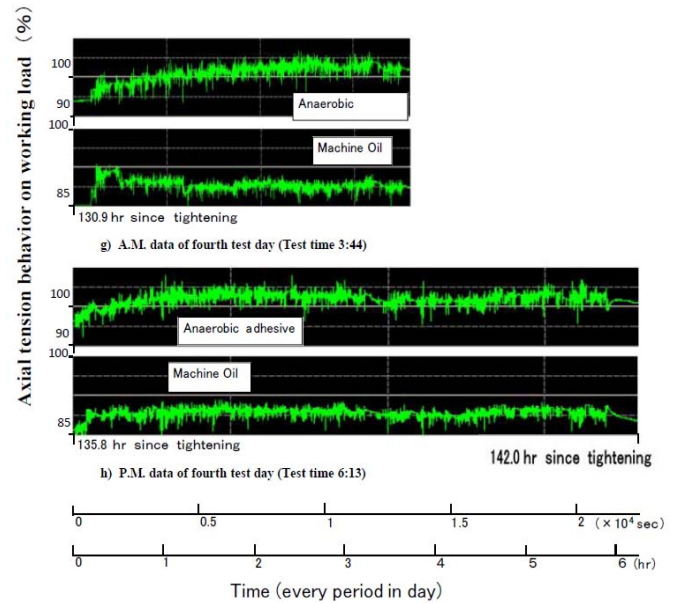

h) P.M. data of fourth test day (Test time 6:13)

Fig. 5-(3): Working load type loosening (Linear coordinates)
(Axial tension behavior in customer since tightening)

The portion in which axial tension rises is also observed in a waveform. It seems as an increased type waveform in this example as the whole although this axial tension rise phenomenon also has a shocking waveform in part.

Figure 6 shows the axial tension value on the outline of the whole waveform from fig.5 at the machine stop period before machine operation. Because the operator used the test forklift freely, the axial tension waveform seems to vary greatly depending on a posture of forklift at stoppage, inclination of a road surface, internal pressure remaining in cylinder, etc.

The plotting point of the beginning of fig. 6 is an axial tension ratio in the stop posture of the test start previous night. Other plotting points show the axial tension ratio in front of the vehicles operation start of a morning and daytime. The last plotting point shows the axial tension ratio when using a stop posture on a flat road surface by the test staff after the end of vehicles operation of the final day.
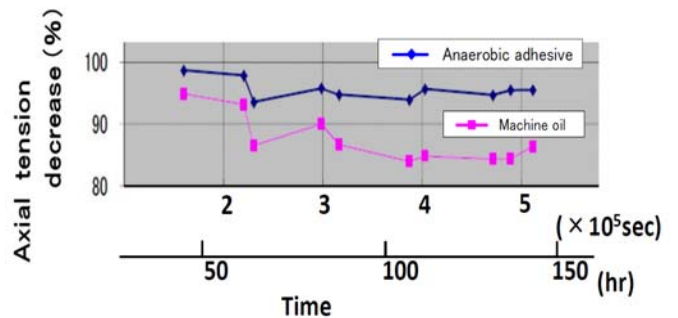

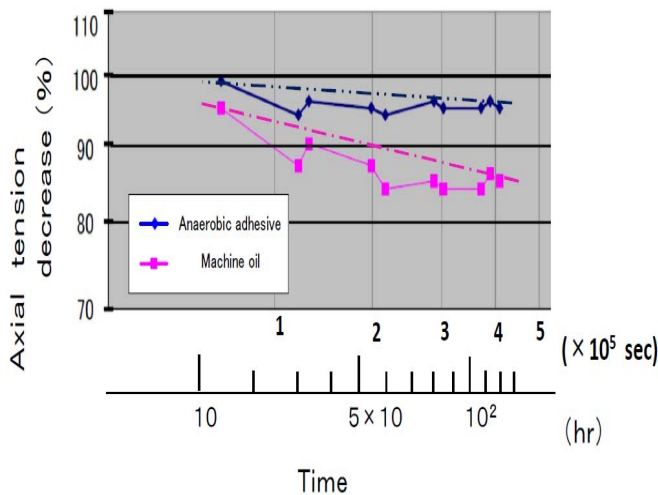**Fig.6:** Outline of whole waveform (Linear coordinates)

5

Fig.7: Outline of whole waveform (Logarithmic coordinates)

If the waveform of fig.6 is expressed as a log-log scale, it becomes the graph as shown in fig.7. It looks that several points are not on linear line because of the road surface and the stop posture and so on. But these points are not over the line. So we judge the waveform is linear, that is the relation of this log-log scale turns into a good linear relation in general, which is same as the report of above-mentioned author[2,3].

The following regression formulas show the relation of these synthetic loosening.

$\log R = A + B \times \log H$ ----- (4)

Here,

H: Operation Interval (hour)

R: (Measured Axial Tension)/(Initial Axial Tension)

A, B, : Constants

Formula (4) is used when operation hours are represented by horizontal axis like this example.

When mileage is represented by horizontal axis like a car, formula (5) is used; when the number of operations is represented by horizontal axis which is convenient for construction machinery, formula (6) will be used.

$\log R = A' + B' \times \log L$ ----- (5)

$\log R = A'' + B'' \times \log N$ ----- (6)

Here, L: Mileage(Km)

N: Number of Operations (Cycle)

R: (Measured Axial Tension)/(Initial Axial Tension)

A', B',A'',B'': Constants

When coefficient of regression lines in Fig.7 is figured out by formula (4), the formulas for lubrication tightening and for anaerobic Adhesive tightening will be as follows respectively.

$100 \times \log R = 15.3 - 11.9 \times \log N$ ・・・・・(7)

$100 \times \log R = 8.09 - 5.86 \times \log N$ ・・・・・(8)

Such regression is used for presumption of a loosening life for the locking devices (parts)/method. Table 3 shows trial calculation conditions for the presumption of a loosening life.

Since the test machine is a large-sized forklift, cycle time is set up for a long time than standard time. As shown in table 4, the trial calculations of the point estimate of the axial tension decreasing rate one month later, one year later, five years later, and ten years later are made.

The axial tension is maintained to about 40% in one year with lubrication tightening. Even if ten years passed, it is presumed that initial axial tension is kept to 30%. On the other hand, initial axial tension will decrease to about 65% in one year with anaerobic adhesive tightening, and it will decrease to about 55% in ten years.

Later in the discussion chapter, it describes the evaluation basis on how far should any residual axial tension be.

Table 3: Trial calculation conditions for the presumption

Prediction Condition Items	Prediction Condition(Time)	Prediction Condition(Number)
Cycle Time of 1 Operation	120(sec)	120(sec)
Operation Times / Day	6 (hour)	6 (hour)
Operation Days / Month	25 (day)	25 (day)
Operations / Mounth	150(hour)	4, 500(cycle)
Operations / 1 Year	1, 800(hour)	54, 000(cycle)
Operations / 5 Years	9, 000(hour)	270, 000(cycle)
Operations / 10 Years	18, 000(hour)	540, 000(cycle)

Table 4: Result of trial calculation

Prediction Interval	Operations time (hour)	Prediction of Axial Tension Decrease R(%)	
		Machine oil	Anaerobic adhesive
1 Mounth	150	52. 4	73. 6
1 Year	1, 800	39. 0	63. 6
5 Year	9, 000	32. 2	59. 9
10 Year	18, 000	29. 7	55. 6

CLASSIFICATION OF DEPRESSION TYPE AND WORKING LOAD TYPE LOOSENING

As shown in the last paragraph, when a depression type loosening tendency and working load type loosening can be observed at the same period in early stages of product development, the future amount of axial tension decrease (grade of loosening) can be presumed by the regression expressed by formula (4) to formula (8).

On the other hand, observation of depression type and working load type loosening may have to be carried out at another time. In such a case, future axial tension decrease/residual axial tension (the grade of the loosening) will be figured out as the sum of each presumed result.

The grade of depression type loosening can be predicted by regression formula (1) with the observation result of the depression phenomenon in early stages of bolting arranged on logarithmic coordinates.

The grade of the depression type loosening included in fig. 7 is separable by use of the above-mentioned formula (1).

The grade of the depression type axial tension decrease after the lapse of about 250-hours after the end of actual machine operation at a customer's site can be figured out by formula (3) and formula (4). On the other hand, the grade of synthetic loosening (axial tension decrease) can be presumed by formula (7) and formula (8). As shown in Table 5, if depression type loosening is deducted from worked type loosening, the rate of working load type loosening is reckonable.

Table 5: The rate of working load type loosening

Tightening method	Calibrated wrench method	
Tightening condition (lubrication)	Machine oil	Anaerobic adhesive (LOCTITE #262)
Total test time (Data observation)	125 hour (c.f. Fig.6 and Fig.7)	
Observation time for depresion type loosening data	13 hour (c.f. Fig.3 and Fig.4) (use for regression formura(2) & (3))	
Observation time for working load type loosening data	25 hour (c.f. Fig.5) (use for regression formura(7) & (8))	
Total time for depresion type loosening	100 hour (=125-25 hour)	
Final residual axial tension in observation time a_1 (at 125 hr)	86.41%	95.50%
Total residual axial tension in depression type loosening a_2 (at 100 hr by regression formura(2) & (3))	93.17%	98.35%
Total residual axial tension in depression type loosening a_3 (at 125 hr by regression formura(2) & (3))	93.34%	98.38%
Total loosening axial tension in depression type loosening during actual machine operation $b_1=a_3-a_2$	0.17%	0.03%
Total loosening axial tension in working load type loosening b_2 $b_2=(a_2-a_1)-(a_3-a_2)$	6.59%	2.82%
Total loosening axial tension during actual machine operation b_3 $b_3=b_1+b_2$	6.76%	2.85%

In this report, as synthetic loosening (total axial tension decrease ratio), the life of locking devices/method can already be presumed, as shown in Table 4. However, the working load type loosening may have to be measured separately for a short

time, and it may have to dissociate from depression type loosening in early stages of product development.

The loosening life presumption method of such working load type loosening is described next chapter.

ANALYSIS FOR FREQUENCY DIAGRAM AS AXIAL TENSION DECREASE OF WORKING LOAD TYPE LOOSENING PHENOMENON

Figure 8 is the enlarged view of fig. 5-a). As mentioned above, shocking loosening (axial tension decrease) is seen here and there in the waveform like an example shown by the enclosure line of the ellipse with a lubrication tightening bolt. What is happening at the screw flanks at this time? In the typical case of lubrication by machine oil the screw thread flank is separated momentarily by external force and the decrease in axial tension has taken place. Or, the vertical force or horizontal force which is added to a screw flank surface decreases, and then bolt and nut rotates relatively in a general understanding.

On the other hand, with the anaerobic adhesive tightening (LOCTITE #262) bolt, although there is a momentary axial tension decrease, it has returned immediately afterwards.
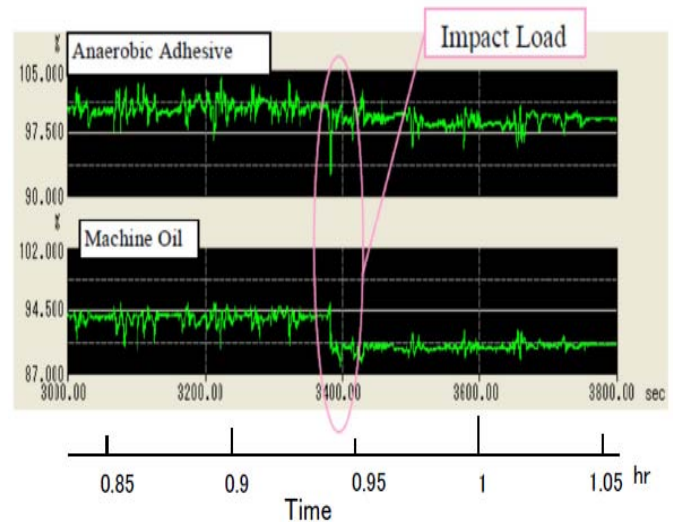

Fig. 8: Enlargement of impact waveform (Linear coordinates) (A.M. data of first test day)

Calculation of the shocking amount of axial tension decrease is done using the actual machine operation waveform of fig. 5. And the amount of axial tension decrease is arranged for every window size of the axial tension. Table 6 shows the total of the loosening frequency count added up.

The mean value in table 6 multiplied the shocking loosening wave value of fig.5 (%) by initial axial tension shown in Table 2. This loosening frequency table shows the result of calculation of the shocking amount of loosening in the axial tension decrease phenomenon for every window size of an axial tension decrease value.

Table 6: Loosening frequency count

a) Machine oil

No.	Mean value (N)	Mean value (%)	Window (N)	Loosening frequency count
9	2,550	4.01	2,400-2,700	2
8	2,250	3.54	2,100-2,400	1
7	1,950	3.07	1,800-2,100	3
6	1,650	2.59	1,500-1,800	2
5	1,350	2.12	1,200-1,500	1
4	1,050	1.65	900-1,200	1
3	750	1.18	600-900	3
2	450	0.71	300-600	12
1	150	0.24	0-300	4
Total axial tension decrease c (kN) [%]				(27.15kN) [42.6%]

c.f.) Mean value (%)=100×Mean value (N)/(1,000×Initial axial tension(63.6kN))

b) Anaerobic adhesive

No.	Mean value (N)	Mean value (%)	Window (N)	Loosening frequency count
2	450	0.82	300-600	1
1	150	0.27	0-300	10
Total axial tension decrease c (kN) [%]				(1.95kN) [3.8%]

c.f.) Mean value (%)=100×Mean value (N)/(1,000×Initial axial tension(55.2kN))

The total amount c of axial tension decrease shown in table 6 calculates by a formula (9).

$$c = \Sigma(\text{Mean value}) \times (\text{Loosening frequency}) \cdots (9)$$

As mentioned above, the impact axial tension increase is also observed in the axial tension rise side (tightness side) partly. However, it is a gradual increase tendency as a whole in general.

So, in this report, frequency calculation of the axial tension increase side is not done. But, finally it is considered as a correction coefficient.

PRESUMPTION FOR THE WORKING LOAD TYPE LOOSENING LIFE BY L-N DIAGRAM AND DEGREE OF LOOSENING DAMAGE

Figure 9 is a L-N diagram (Loosening Life --- Numbers of Cycles to Loosening, N Diagram) proposed by this paper.
The diagram is created as follows.
(1) Axial tension will be lost if the shocking axial tension decrease is equivalent to 100% of initial axial tension.
The axial tension decreasing rate at that time is 100%, and axial tension residual ratio is 0%.
(2) Axial tension is lost if the shocking axial tension decrease equivalent to 1% of initial axial tension is received 100 times.
(3) If there are 80 shocking axial tension decrease equivalent to 1% of initial axial tension, an axial tension decreasing rate is 80%, and axial tension residual ratio is 20%.

(4) The relation between the degree of cumulative loosening damage, test time, and a loosening life has an alignment relation in the log-log paper like an axial tension decreasing rate and the relation of time.
(5) The time when the extension of the regression line of the degree of cumulative loosening damage and test time reaches the degree 1 of loosening damage, and it becomes a loosening life for locking devices (parts)/method . A loosening life can be searched for every axial tension decreasing ratio (or every ratio of residual axial tension).

By such a method, 0%, 20%, 40%, 60%, 80%, and 90% of line is pulled with the residual axial tension rate in the fig.9. Each line will turn into 100%, 80%, 60%, 40%, 20%, and 10% of line for axial tension decrease ratio relatively. The tolerance of these axial tension decreasing rates or axial tension residual ratio will be a base of the evaluation value (evaluation diagram) of loosening.

Generally, loosening occurs when residual axial tension has been lost. But in some case, the function may be lost when the level which has residual axial tension depending on the characteristic of a product or a component is reached. In such a case, the evaluation index is not only 0% but is available such as 20% 40% 60% 80% etc.
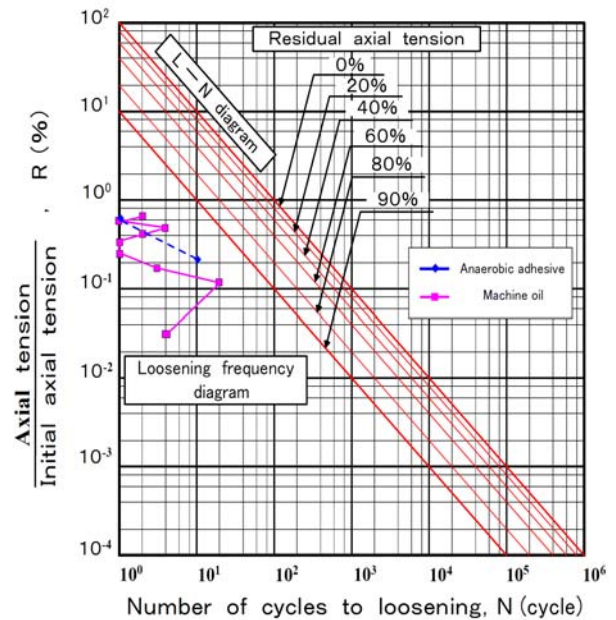

Fig.9: L-N diagram

The formula (10) mathematizes the L-N diagram of fig. 9. The constants of formula (10) are shown in Table 7.
$$\log R = p + q \times \log N \text{ ----- (10)}$$
Here,
N: Number of cycles to loosen (Cycle)
R: (Axial tension)/(Initial axial tension)
p,q: Constants

Copyright © 2012 by ASME

Table 7: The constants of formula (10)

Residual axial tension ratio(%)	Axial tension decrease ratio(%)	Constant for formula(10)	
		p	q
0	100	2	-1
20	80	1.903	-1
40	60	1.778	-1
60	40	1.602	-1
80	20	1.301	-1
90	10	1	-1

By the way, the total amount c of loosening shown in Table 6 is the big value. Therefore, it will loosen immediately.

It is because the cause has not been taken into account in the phenomenon for an axial tension increase. The correction coefficients in consideration of the point analyze according to the following process.

(1) Although depression type loosening is also included in the working waveform shown in fig. 5, it is treated as a slight quantity (negligible).
(2) Total amount of axial tension decrease c (%) for which it calculated in formula (9) is equivalent to the value of b_2 in table 5.
(3) The correction coefficient d is $d = b_2/c$.

Table 8 is the result of correction coefficients calculated based on this view. From them, table 9 is the calculation result of the degree of damage of loosening at residual axial tension ratio 0% for example. The frequency count value by Table 9 is also combined in fig.9 as loosening frequency diagram.

These relations are obtained and created by the hint in the relation between the S-N diagram by Miner's rule and cumulative damage models used by fatigue life estimation and stress frequency count.]

The similarity of the formula of life prediction (fatigue and loosening) is as follows.

(1) The stress frequency diagram of fatigue strength and the axial tension frequency diagram of loosening
(2) S-N diagram and L-N diagram
(3) The degree of cumulative damage for fatigue strength and cumulative damage of loosening damage

Table 8: correction coefficient

Tightening condition (Lubrication)	Observation time (hr)	Total Axial tension decrease (Table 5)	Total Axial tension decrease (Table 6)	Correction coefficient
Machine oil	25	6.59%	42.60%	0.155
Anaerobic adhesive	25	2.82%	3.80%	0.742

The degree of cumulative loosening damage D_1 calculated by formula (11).

$$D_1 = \Sigma\,(n_i / N_i) \quad \cdots\cdots (11)$$

The net test time of working load type loosening is 25Hr from Table 5.

Table 9: degree of loosening damage and loosening life estimation

a) Machine oil tightening

No.	Corrected window (N)	Axial tension ratio (%)	L-N diagram frequency count Ni	End of 1st day cumulative count	Damage ΣDi	End of 2nd day cumulative count	Damage ΣDi	End of 3rd day count	Damage ΣDi	End of 4th day count	Damage ΣDi
9	404	6.36×10^{-3}	1.6×10^2	1	0.00625	1	0.00625	2	0.01250	2	0.01250
8	359	5.64×10^{-3}	1.8×10^2	1	0.00556	1	0.00556	1	0.00556	1	0.00556
7	310	4.87×10^{-3}	2.1×10^2		0.00000	1	0.00476	2	0.00952	3	0.01429
6	263	4.13×10^{-3}	2.5×10^2		0.00000		0.00000	1	0.00040	2	0.00080
5	219	3.38×10^{-3}	2.9×10^2		0.00000	1	0.00034	1	0.00034	1	0.00034
4	167	2.62×10^{-3}	3.9×10^2	1	0.00256	1	0.00256	1	0.00256	1	0.00256
3	120	1.89×10^{-3}	5.1×10^2	1	0.00196	2	0.00392	3	0.00588	3	0.00588
2	71	1.12×10^{-3}	8.8×10^2	1	0.00114	5	0.00568	7	0.00795	12	0.01364
1	24	3.78×10^{-4}	2.8×10^3	2	0.00071		0.00000	3	0.00107	4	0.00143
Degree of cumulative damage for loosening ΣDi (Residual axial tension 0%)					0.01818		0.02908		0.04580		0.05700

b) Anaerobic adhesive tightening

| No.	Corrected window (N)	Axial tension ratio (%)	L-N diagram frequency count Ni	End of 1st day cumulative count	Damage ΣDi	End of 2nd day cumulative count	Damage ΣDi	End of 3rd day count	Damage ΣDi	End of 4th day count	Damage ΣDi
2	340	6.13×10^{-3}	1.6×10^2		0.00000	1	0.00625	1	0.00625	1	0.00625
1	110	2.02×10^{-3}	4.6×10^2	4	0.00870	6	0.01304	8	0.01739	10	0.02174
Degree of cumulative damage for loosening ΣDi (Residual axial tension 0%)					0.00870		0.01929		0.02364		0.02799
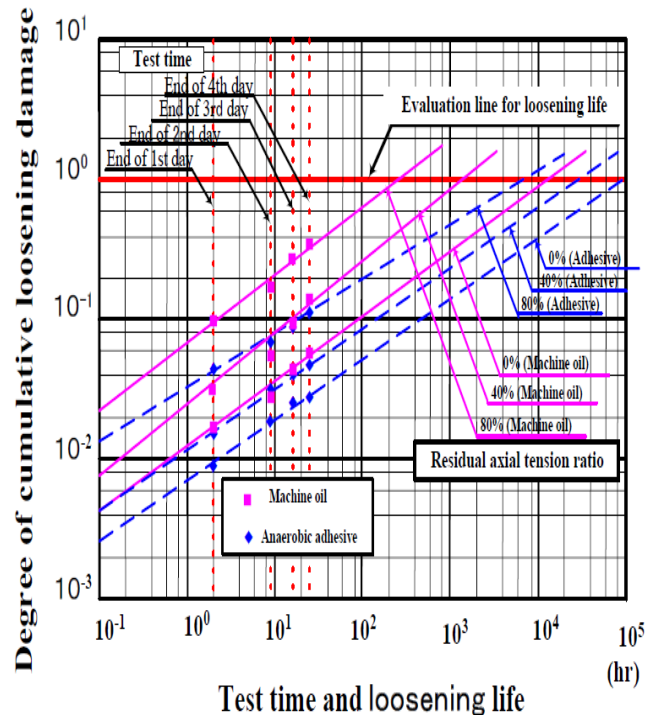
Fig.10: Evaluation of loosening life

Figure 10 shows the relation between the degree of loosening cumulative damage of each test day of Table 9, test time, and a loosening life. The relation when making an axial tension decreasing rate into 40% and 80% is also shown in the figure.

PRESUMPTION OF SYNTHETIC LOOSENING LIFE

As mentioned above, simple presumption of the synthetic loosening life is analyzed as shown in Table 4. The amount of axial tension decrease (grade of loosening) is figured out from a vehicles durable life etc. by fig. 7, formula (6) and formula (7) etc.

On the other hand, depression type loosening and working load type loosening are measured separately, and how to presume each amount of axial tension decrease or the amount of residual axial tension is shown by fig. 4 and table 9 in the foregoing paragraph.

The amount of axial tension decrease in the case of measuring separately depression type loosening and working load type loosening can be presumed by the following methods.

It is considered as the example of machining oil lubrication tightening.

(1) Make allowable residual axial tension of working load type loosening into 60% (the amount of allowable axial tension decrease is 40%).
(2) From fig.10, loosening life is 1,300 hour.
(3) The depression type loosening by 1,300 hour can be found with the axial tension ratio r= 0.92 from regression (2).
(4) The axial tension decrease of depression type loosening becomes 8%.
(5) The sum of working load type loosening by 1,300 hour and depression type loosening becomes 48% (a residual axial tension level is 52%).

The value of total of this loosening, allowable residual axial tension (valuation basis), the durable life of a product, etc. are taken into consideration to determine the synthetic loosening life. A trial-and-error method will be applied and the design of proper locking devices (parts) / method will be advanced.

Although these processes can be mathematized, it is considered as a future subject.

DISCUSSION

Here, let's discuss the research to loosening evaluation and also the evaluation diagram.

EVALUATION OF SELF-LOOSENING

In this paper, loosening phenomenon in the actual machine operation is observed during long-term operation with the test equipment and test spot (customer's site). Aiming to establish the absolute evaluation standard, an evaluation diagram is proposed for absolute loosening estimation vs. relative loosening estimation. It deals with the evaluation of loosening when locking device (method) is used on the actual machine.

As shown in Fig. 11, the locking effect performance is evaluated for an example [21]. In arrangement of this kind of test result, a vertical axis takes clamping force (residual axial tension) in many cases.
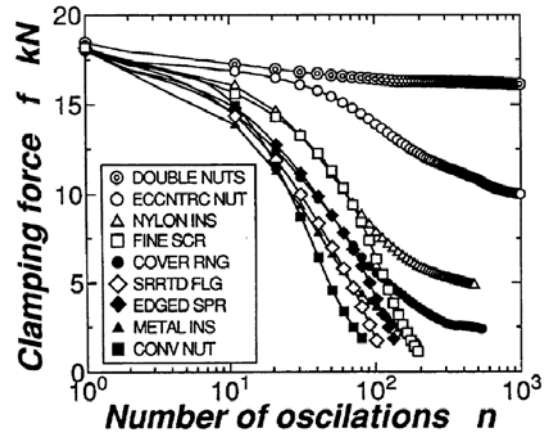

Fig.11: Result of loosening test (for example) [21]

Fig.12: Loosening behavior from testing machine[23]

However, these estimation methods are just the evaluations on performance of locking devices in laboratory test. They enable qualitative evaluation as well as relative comparison on loosening-preventive performance of locking parts(devices) quantitatively. Yet, they cannot perform absolute evaluation on whether the bolted joint makes specified performance and maintains its initial performance after lapse of certain period of time during actual machine operation.

EVALUATION DIAGRAM

By the way, the loosening waveform as shown in fig. 10 is observed in the investigation of screw loosening using the loosening test machine. Initial axial tension is considerably lost immediately after the test start as shown in the waveform, but loosening has stopped after that. On the other hand, the loosening waveform as shown in Fig. 12 is observed in the investigation of screw loosening using the loosening test machine; which it is conducted by the Japan

Research Institute for Screw Threads and Fasteners (JFRI)[23]. Figure shows that loosening has taken place catastrophically. It should never reach this catastrophic point (Transition Point) in self-loosening during actual machine operation. Then, the bolted joints loosening is classified into gradual decrease loosening region I and catastrophic loosening region II as shown in fig. 13. Because of this classification, locking device (method) in bolted joint should be allowed to be used only in gradual decrease loosening region I. From these loosening test results, the next subject for loosening investigation is getting to know the characteristic of a transition point in the diagram shown in the fig. 14 for example, such as a decreasing rate for the mileage (or time, the number of operation, etc.) from initial axial tension.
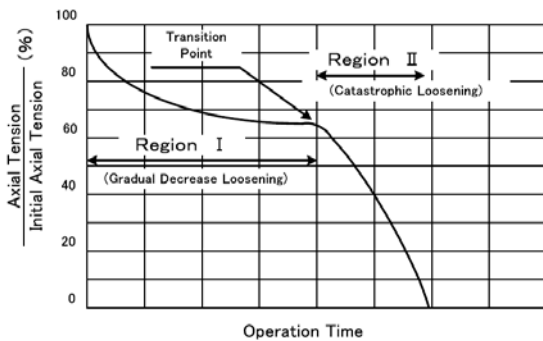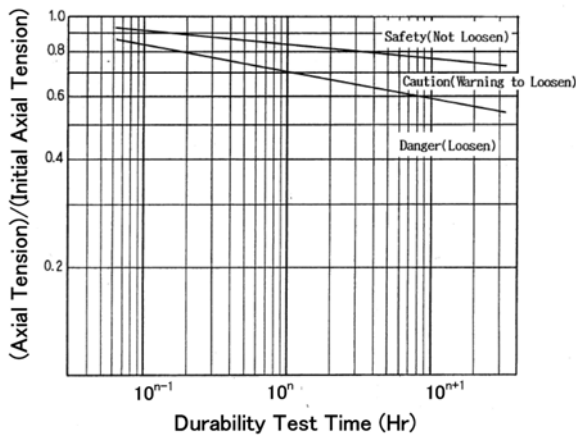

Fig.13: model of loosening test result

Fig.14: Loosening evaluation diagram
(Logarithmic coordinates)

CONCLUSIONS

In evaluation for the performance of locking devices (parts) / method, absolute evaluation is indispensable. In this paper, the research and examination is performed from this viewpoint. The knowledge acquired by this research is arranged below.

(1) This paper presents a method for estimating the absolute lock effect in bolted joints during actual machine operation.

(2) Loosening phenomenon of bolted joint is divided into a depression type (static) and working load type loosening (dynamic).

(3) The loosening phenomenon of bolted joint is grasped with the decrease tendency of the initial axial tension or residual axial tension.

(4) The loosening phenomenon is a good linear relation on logarithmic coordinates (log-log paper) between the decrease of axial tension (measured tension/initial axial tension) and number of operations (or working time or mileage)since last tightening.

(5) Based on this relation and observation of loosening in the early stages of product development, we estimate the rate of axial tension decrease (self-loosening level) accurately after prolonged operation since tightening by measuring the initial axial tension behavior by using the proposed regression formula.

(6) The trial calculation of the residual axial tension after prolonged operation is made using the industrial vehicle (stacking capacity 16 ton large-sized forklift-truck) at customer's site by loosening measurement,.

(7) Using only few days' data, it is presumed that the initial axial tension is maintained to 55% or more in case of anaerobic adhesive tightening and almost 30% in case of lubrication tightening after ten years.

(8) In development phase of actual machine, data collection may be performed simultaneously or separately for both types of loosening at different times. Propose the method of presuming the grade and loosening life data collected at different times. Synthetic loosening can be estimated as the sum of depression type and working load type loosening.

(9) In the working load type loosening, authors propose the L-N diagram (Loosening Life - Numbers of Cycles to Loosening N Diagram) for loosening life estimation like the S-N diagram for fatigue life estimation and loosening frequency diagram. Using the loosening frequency diagram and L-N diagram, the degree of loosening damage for every axial tension residual ratio can be figured out to analyze the loosening life of the locking device/method by Miner's rule and cumulative loosening damage models.

(10) We discuss the possibility of association between relative evaluation of loosening tendency and absolute evaluation of the laboratory loosening test and actual machine operation.

Application in a design phase is a research task of the following step also.

REFERENCES

[1] Hareyama,S., Kodama,S., 1990, A Study on Confidence Limit for Two Independent Probability Variables in Engineering Problems (Applications to Limit of Transmitted Torque in Disk Cluch and Bolt Axial Tension Control), JSME International Journal(SeriesⅢ) ,Vol.33, No.2, pp.256-262.

[2] Hareyama,S., Hamada,H., Ishimaru,G., 1988, Self Loosening and Strength Estimation of Bolted Joint under Machine Operation (1st Report , Absolute Estimation on the Self Loosening) (in Japanese),Transaction of JSME (Series C), Vol.54, No.503 , pp.1559-1563.

[3] Hareyama,S.,Takada,R.,Shimodaira,T.,Tamura,K.,Hoshi,A., Nakashima,M., 2012, A Proposal for the Absolute Estimation Method on Self-loosening of Bolted Joints during OFF-road Vehicle Operation, International Journal of Automotive Engineering,Vol.3, No.1, pp.47-53.

[4] Junker,G.H., Williams,D.A., 1973, Rules for design and calculation of high-duty bolted joints(PART ONE:BASIC DESIGN), Sub Assembly , Vol.11. No.3, pp.22-24.

[5] Junker,G,.H., 1969, New Criteria for Self-Loosening of Fasteners Under Vibration, SAE Transactions, No.690055, pp.314-335.

[6] Clark,S.K., Jerald,J.K., 1966, Vibratory Loosening of Bolts, SAE Transactions, No.660432, pp.1-10.

[7] Hongo,K., Loosening and Locking Devices of Bolt-Nut Units (in Japanese), Science of Machine , Vol.14,No.1(1962), pp.231-238.

[8] JFRI Committee for Research of Bolt Tightening, 1980, A Research for Tightening Characteristics of High Strength Bolts (Report Ⅲ) (in Japanese), The Japan Research Institute for Screw Thread and Fasteners(JFRI), pp.56.

[9] Yamamoto,A., 1972, Loosening of Bolted-Joints (in Japanese) , Fastening & Joining, No.2, pp.1-5.

[10] Shoji,Y., Sawa,T.,2005, Analytical Research on Mechanism of Bolt Loosening Due to Lateral Loads, ASME PVP (Pressure Vessels and Piping), No.PVP2005-71333, pp.1-7.

[11] Vinogrodov,O., Huang,X., 1989, On a High Frequency Mechanish of Self-Loosening of Fasteners, ASME Design Engineering Division,Vol.18,No.4, pp.131-137.

[12] Daadbin,A., Chow,Y.M., 1992, A Theoritical Method to Study Thread Loosening, Mechanism and Machine Theory, Vol.27,No.1, pp69-74.

[13] Hess,D.P.,.Sudhirkashyap,S.C., 1997, Dynamic Loosening and Tightening of Single-Bolt Assenbly, Transaction of the ASME.Journal of Vibration and Acoustics, Vol.119,No.3, pp.311-316.

[14] Zadoks,R.I., Yu,X., 1993, A Preliminary Study of Self-Loosening in Bolted Connections, ASME Design Engineering Division,Vol.54, pp.79-88.

[15] Izumi,S., Yokoyama,T., Iwasaki,A., Sakai,S., 2005, Three-Dimensional Finite Element Analysis of Tightening and Loosening Mechanizum of Threaded Fastener, Engineering Failure analysis ,Vol.12 No.4, pp604-615.

[16] Nishimura,N., Hattori,T., Yamashita,M., Hayakawa,N., 2007, Sliding and Loosening Behavior of Threaded Joints under Transverse Loading, Key Engineering Materials,No.353/358 Pt.2, pp.894-897.

[17] Hongo,K., 1964, Loosening of Bolt and Nut Fastening (in Japanese), Transaction of JSME(Series Ⅰ), Vol.30,No.215, pp.934-939.

[18] Yamamoto,A., 1969, Loosening of Bolted-Joints and evaluation of locking effect for many kinds of locking devices(2) (in Japanese) , Fastening & Tecnology, Vol.10,No.6, pp.23-33.

[19] Kasei,S., 1985, Loosening and Locking Technology of Bolted-Joints(in Japanese), Science of Machine , Vol.37,No.8, pp.21-26.

[20] Kumakura,S., Hosokawa,S., Sawa,T., 1998, Bolt Load Reduction of Bolted Joints under External Axial Load ,ASME PVP (Pressure Vessels and Piping) ,No.367,pp.103-108.

[21] Sase,N., Koga,S., Nishimura,K., Fujii,H., 1996, Evaluation of Anti-Loosening Nuts for Screw Fastener ,Journal of Material Processing Technology , 56.1/4,pp321-332.

[22] Zhao,Y.,Lee,C.,Che,X.,Yee,C.,1999,Prediction of Stabilizer Bar Retention Bracket Bolt Looseness , ASME PVP (Pressure Vessels and Piping) ,PVP-Vol.382,pp.161-167.

[23] JFRI Committee for Research of Bolt Tightening, 1980, A Research for Tightening Characteristics of High Strength Bolts (ReportⅢ) (in Japanese), The Japan Research Institute for Screw Thread and Fasteners(JFRI), pp.56.