Proceedings of the ASME 2016 International Mechanical Engineering Congress and Exposition
IMECE2016
November 11-17, 2016, Phoenix, Arizona, USA

IMECE2016-66336

# EXPERIMENTAL STUDY TO VERIFY ELLIPTICAL CONFIDENCE LIMIT METHOD FOR BOLTED JOINT TIGHTENING

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## ABSTRACT

The calibrated wrench method is often used for tightening. When tightening bolted joints, it is important to apply high axial tension. However, since the axial tension is indirectly applied in this method, it varies and has a distribution in the case of tightening carried out in the production line of a factory, for example. However, the calibrated wrench method is still widely used because of the simple tool and easy standardization. In our previous papers, we analyzed and discussed the main points of this research by a theoretical approach as discussed below. Conventionally, this type of distribution has been considered to lie within a rhombus (more precisely, within a rectangular area). However, when considering the tightening torque and axial tension as independent random variables, the distribution becomes elliptical. The same idea applies to the relation between the tightening torque and the equivalent stress for a bolt axis based on shear strain energy theory. On the other hand, regarding the variation in the tightening torque (tightening work coefficient ***a***) actually applied to a bolt, it was reported by Bickford, Kawasaki, and others that it can vary by 15% or more from the target (indicated) tightening torque. However, the torques for wrenches used at actual assembly sites or under lubricated conditions were not reported. Therefore, it is necessary to experimentally verify that the relation between the tightening torque and the axial tension (axial stress) and equivalent stress of a bolt axis is distributed in an ellipse. Furthermore, the screw-thread characteristics (torque coefficient, equivalent stress coefficient, coefficient of friction, etc.) during the tightening process should be clarified by an experimental approach and observation. Thus, in this study, in experiments under dry (as-obtained) and lubricated (Loctite 263) conditions, the tool (preset-type and dial-type torque wrenches) and bolt strength classification (8.8 and 10.9) were changed, and the screw-thread characteristics were observed during actual bolt tightening and the characteristics under different conditions were analyzed. It was clearly shown that the tightening torque and the axial tension (axial stress) of a bolt axis and the equivalent stress vary with an elliptical distribution rather than a rhombic distribution. Finally, the validity of the tightening theory based on the elliptical confidence limit method was also verified experimentally.

## INTRODUCTION

Screw threads and bolted joints play an important role in many industrial products such as cars, construction equipment, industrial machines, electrical machinery, hydraulic equipment, airplanes, and plant equipment. Although screws and bolts are machine parts made by a simple principle involving a wedge and a spiral and have been in use for more than 2000 years, problems such as poor bolting, self-loosening, and insufficient strength occur even today.

Why do problems with screw threads still occur? Why do they continue to be a machine element requiring special attention? The basic problems in bolted joints are given below, as described in our previous papers [1][2].

1) How to maintain tightening reliability.
2) How to prevent breakage (fatigue breakage, etc.).
3) How to prevent loosening failure.
4) Others.

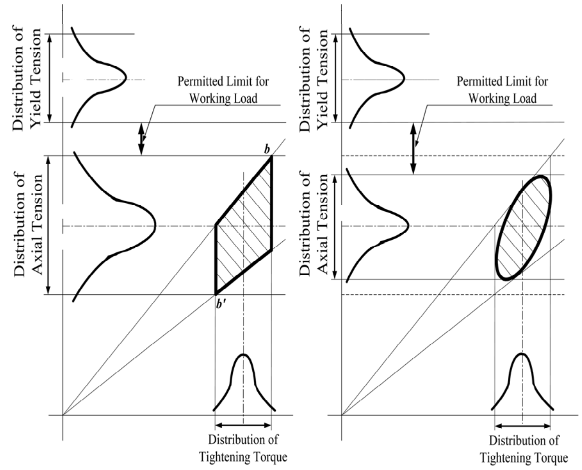
We have also previously presented a loosening lifetime prediction method [3] and a working load analysis and fatigue lifetime prediction method for bolted joints [4].

Concerning tightening reliability, many studies have been conducted, for example, Bickford [5] described the theory of tightening. Also in recent research, Nassar and coworkers [6][7] theoretically investigated the torque-tension relation in terms of the thread friction torque and tightening speed. Amir et al. [8] predicted the failure of bolted joints using Von Mises stress. Kopfer et al. [9] investigated the effect of the preload history on the lifetime of a product used in fastening systems. Hoernig et al. [10] derived torque and preload equations and the thread friction coefficient at the thread. Hemminger [11] presented the results of an experiment on tightening characteristics.

The purpose of this study is to examine the problem of ensuring tightening reliability in bolted joints. The fundamental concept is as follows. At sites where a large number of bolted joints are tightened, it has been conventionally thought that when the axial tension (clamping force) is plotted against the tightening torque, the distribution has a rhombus shape as shown in Fig. 1(a). However, when considering the tightening torque and the axial tension as independent random variables, the distribution becomes elliptical as shown in Fig. 1(b).

The same concept can be used to obtain the relation between the tightening torque and the equivalent stress based on shear strain energy theory. The permissible margin of stress created by an external force and the confidence limit of the distribution for a large number of tightened bolts should be taken into consideration. Updated knowledge on the reliability of bolted joints tightened by the calibrated wrench method was presented theoretically in our previous papers [1][2]. A method of computing the optimum tightening torque was also developed through the verification of this method. On the other hand, regarding the variation in the tightening torque (tightening work coefficient ***a***) actually applied to a bolt, it was reported by Bickford [12], Kawasaki [13], and others that it can vary by 15% or more from the target (indicated) tightening torque. However, the torques for wrenches used at actual assembly sites or under lubricated conditions were not reported.

Therefore, it is necessary to experimentally verify that the relation between the tightening torque and the axial tension (axial stress) and equivalent stress of a bolt axis is distributed in an ellipse. Furthermore, bolted-joint screw-thread characteristics (torque coefficient, equivalent stress coefficient, coefficient of friction, etc.) during the tightening process should be clarified by an experimental approach and observation.




a) Rhombic (Conventional) b) Elliptical (Proposed)

**Fig. 1:** Relation between tightening torque and axial tension (conventional method vs proposed method)

Thus, in this study, in experiments, the lubrication conditions, tool, and bolt strength classification were changed, and the screw-thread characteristics were observed during actual bolt tightening, and the characteristics under different conditions were analyzed. It was clearly shown that the tightening torque and the axial tension (axial stress) of a bolt axis and the equivalent stress vary with an elliptical distribution rather than a rhombic distribution.

The results of this study are expected to contribute to improving the tightening reliability of bolted joints.

## NOMENCLATURE

$T$ : tightening torque
$T_l$ : loosening torque
$T_1$ : torque component used to overcome friction between male and female thread flanks
$T_2$ : torque component used to create axial tension and joint clamping force $P$
$T_3$ : bearing friction torque component used to overcome friction between turning bolt head or nut and clamped joint surface
$T_s$ : torque used to twist body of bolt (torsional torque)
$T_{mean}$ : target tightening torque (or value of torque given to a worker
$P$ : axial tension (clamping force)
$d$ : nominal diameter
$d_1$: basic minor diameter of external thread
$d_2$ : basic pitch diameter of external thread
$d_3$ : minor diameter of external thread
$d_s$ : diameter of stress area
$d_w$ : equivalent bearing-surface diameter of friction torque
$d_b$: bolt shaft axis diameter

$A_s$ : stress area
$H$ : fundamental triangle height ($0.866025p$)
$p$ : pitch
$\alpha$: half of thread angle
$\beta$: lead angle
$\varphi'$ : friction angle of triangular screw thread flank
($\varphi'=\tan^{-1}(\mu_s \sec\alpha)$)
$K$ : torque coefficient (nut factor)
$K_1$ : torque coefficient between screw flanks
$K_2$ : axial-tension torque coefficient
$K_3$ : bearing-surface torque coefficient
$Ks$ : torsion torque coefficient ($K_s=K_1+K_2$)
$k$ : axial tension factor
$\eta$ : torsion torque ratio ($\eta=K_s/K$)
$\mu_s$ : coefficient of friction between screw flanks
$\mu_w$ : coefficient of friction at bearing surface
$\mu$ : coefficient of friction ($\mu=\mu_s=\mu_w$)
$\sigma_e$ : equivalent stress based on shear strain energy theory
$\sigma$ : axial stress of screw thread in stress area
$\tau$ : shear stress of screw thread in stress area
$\psi_e$ : equivalent stress coefficient
$\sigma_{ymin}$ : lower limit of yield point
(or stress at 0.2% non-proportional elongation)
$a$ : tightening work coefficient
$c$ : initial equivalent stress ratio
$c'$ : true initial equivalent stress ratio
$c_0$ : initial axial stress ratio
$c'_0$ : true initial axial stress ratio
$E_b$: Young's modulus of bolt shank
$E_c$: Young's modulus of tightened bracket
$I_p$: polar moment of area of bolt shaft
$f(T)$: probability density function (pdf) of tightening torque $T$
$g(\psi_e)$: pdf of equivalent stress coefficient $\psi_e$
$r_e$, $r_T$ , $r_{\psi e}$ : random variables of $\sigma e$, $T$, and $\psi_e$, which serve as standard scores of a normal distribution
$r_P$, $r_K$ : random variables of $P$ and $K$, which serve as standard scores of a normal distribution
$\theta$ : angle giving point $s(T,\psi_e)$ on elliptical confidence limit
$\theta_e$ : angle corresponding to coordinates of point $s(T,\psi_e)$ on elliptical confidence limit giving maximum equivalent stress (see Fig. 2)
$\theta_p$ : angle giving maximum and minimum of axial-tension distribution on elliptical confidence limit

## TIGHTENING THEORY UNDERLYING CALIBRATED WRENCH METHOD

As shown in Fig. 2, the strain gauges at the measurement points are assumed to be arranged so that strain gauges measuring the strain along three orthogonal axes are bonded to the bolt axis at A and B to prevent any effect of the bending moment. The strains in the three orthogonal directions measured by the strain gauge at A, $I$, $II$, and $III$, for example, are denoted as $\varepsilon_{AI}$, $\varepsilon_{AII}$, and $\varepsilon_{AIII}$,

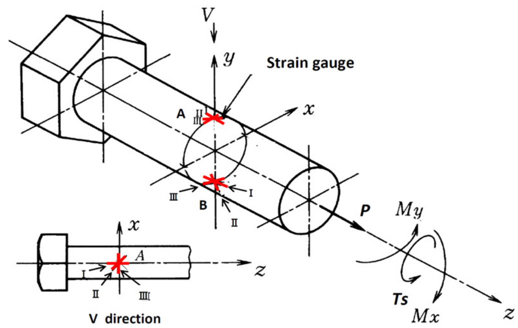



**Fig. 2:** Locations of strain gauges used for measurement

respectively. Then, the loads applied to the bolted joint are characterized as follows.

$$\left.\begin{aligned} \varepsilon_I &= (\varepsilon_{AI}+\varepsilon_{BI})/2 \\ \varepsilon_{II} &= (\varepsilon_{AII}+\varepsilon_{BII})/2 \\ \varepsilon_{III} &= (\varepsilon_{AIII}+\varepsilon_{BIII})/2 \end{aligned}\right\}\cdots\cdots(1)$$

The axial tension (clamping force), which is the axial stress, is obtained as

$$P=A_b\sigma=\pi E \varepsilon_I d_b^2/4 \cdots\cdots(2)$$

Also, the shear strain $\gamma$ of the bolt shaft surface is obtained from Mohr's strain circle as

$$\gamma=\varepsilon_I+\varepsilon_{III}-2\varepsilon_{II} \cdots\cdots(3)$$

Then, the torsional torque and shear stress $\tau$ are obtained by the following equation based on Hooke's law:

$$Ts=\tau Ip/(d_b/2)=G\gamma Ip/(d_b/2), \cdots\cdot(4)$$

where $Ip=\pi d_b^4/32$.

Then the axial stress $\sigma$ is obtained as

$$\sigma=\frac{P}{A_S}=\frac{4T}{\pi d_S^2 \cdot d\cdot \mathrm{K}}, \cdots\cdots \quad (5)$$

where

$$A_s=\frac{\pi}{4}d_s^2, \; d_s=\frac{d_2+d_3}{2}, \; d_3=d_1-\frac{H}{6},$$

and the shear stress $\tau$ is obtained as

$$\tau=\frac{16\,T_s}{\pi d_s^3}=\frac{16\,\eta\,T}{\pi d_s^3}\cdots\cdots \quad (6)$$

Generally, for example referred in our previous paper [1][2], the relation between the tightening torque $T$ and axial tension $P$ for a triangular screw thread is theoretically expressed as

$$\left.\begin{aligned} T&=KPd=(K_1+K_2+K_3)Pd \\ &=\frac{d_2}{2}\left(\mu_s \sec\alpha+\tan\beta+\frac{d_w}{d_2}\mu_w\right)P \\ &=\frac{1}{2}(\mu_s d_2 \sec\alpha+p/\pi+d_w\mu_w)P. \\ &\text{where } \tan\beta=p/(\pi d_2) \\ &\text{In case of loosening, loosening torque } T_l \\ &(T_l \text{ takes a negative value) is expressed as} \\ T_l&=\frac{1}{2}(\mu_s d_2 \sec\alpha-p/\pi+d_w\mu_w)P. \end{aligned}\right\}\cdots\cdot(7)$$

Then, the friction coefficients are obtained as

$$\left.\begin{aligned} \mu_s &= 2d\left(T_s/(Pd)-K_2\right)/(d_2 \sec\alpha) \\ \mu_w &= (2d/d_w)(K-T_s/(Pd)) \\ \mu &= \frac{2Kd - d_2\tan\beta}{d_2\sec\alpha + d_w}. \end{aligned}\right\} \cdots\cdots(8)$$

When $\mu=\mu_s=\mu_w$, the torque $T_s$ exerted on the torsion of a bolt during tightening is expressed as

$$T_s = (K_1+K_2)Pd = K_s Pd = \eta T \cdots\cdots (9)$$

When the breakage of a bolted joint made of mild steel or carbon steel is explained in accordance with shear strain energy theory (the von Mises yield criterion), the relation between the tightening torque and equivalent stress is expressed as

$$\sigma_e = \sqrt{\sigma^2+3\tau^2} = \sqrt{\left(\frac{1}{K}\right)^2 + 3\left(4\eta\frac{d}{d_s}\right)^2}\,\frac{T}{A_s d} = \phi_e \frac{T}{A_s d} \cdots (10)$$

For the case that a structure is tightened by a bolted joint, these equations are well established in general tightening theory.

In many studies on tightening carried out in the production line of a factory, for example, it has been supposed that the variation in axial tension is distributed in the form of a rhombus as shown by the hatched area in Fig. 1. Point $b$ in the figure is located at the maximum of the equivalent stress distribution $\sigma_{emax}$ and point $b'$ is the point of minimum equivalent stress $\sigma_{emin}$.

In this case, the maximum equivalent stress coefficient $\phi_{emax}$ can be obtained from $K_{min}$ and $\eta_{max}$ using Eq. (10), and also the minimum equivalent stress coefficient $\phi_{emin}$ can be obtained from $K_{max}$ and $\eta_{min}$.

The variation in the tightening torque of a large number of bolted joints is represented by the tightening work coefficient $\boldsymbol{a}$ given by Eq. (11). The coefficient $a$ depends not only on the tightening tool accuracy but also on the management state, the work posture, and the process control capability of a tool or shop floor at the production site. Bickford [12] has summarized the grade of variation for every tightening tool and work method. According to his classification, about 3-15% ($a$=0.03-0.15) is thought to be sufficient for the tightening work coefficient $a$ in the calibrated wrench method. Bickford indicated that the tightening accuracy can be ±20% ($a$= 0.2) when the accuracy is low. Regarding how to control the quality of screw thread tightening in the production process, Kawasaki et al.[13] was analyzed the concept of classifying the error (variation) for the tightening torque accuracy (±30%, $a$=0.3) of the calibrated wrench method.

$$a = (T_{\max} - T_{\min})/(2T_{mean}) \cdots\cdots (11)$$

$c_{max}$ in Eq. (12) is the ratio of $\sigma_{emax}$ to $\sigma_{ymin}$. The ratio $c$ is determined with consideration of the stress generated in the bolt by an external force. Using this relation, the target tightening value $T_{mean}$ can be expressed by Eq. (13).

$$\sigma_{e\max} = c_{\max}\,\sigma_{y\min} \cdots\cdots(12)$$

$$T_{mean} = \frac{c_{\max}\,\sigma_{y\min}}{(1+a)\phi_{e\max}} A_s d \cdots\cdots (13)$$

## ELLIPTICAL CONFIDENCE LIMIT OF EQUIVALENT STRESS (PROPOSED METHOD) [1]

In this paper, several important equations are shown. When the breakage of bolted joints is explained in accordance with shear strain energy theory, the relation between the tightening torque and the equivalent stress $\sigma e$ is expressed by Eq. (10) as shown in detail in our previous paper[1]. In the equation, the variables describing the dimensions of screw threads, such as the nominal diameter d and stress area $A_s$, can be treated as constants to solve the equation. The coefficient $\phi_e$ essentially becomes a function of $\mu s$ and $\mu w$. On the other hand, the tightening torque $T$ is determined by the length of the torque wrench and the force it exerts. Therefore, it is permissible to consider $\phi_e$ and $T$ as independent random variables.

Now, $f(T)$ has the normal distribution $N(\mu_T, \sigma_T^2)$ and $g(\phi_e)$ has the normal distribution $N(\mu_{\phi e}, \sigma_{\phi e}^2)$. If the equivalent stress $\sigma_e$ has the normal distribution $N(\mu_v, \sigma_v^2)$, and if the equivalent stress $\sigma_e$ is also expressed by the equation $\sigma_e = \mu_v + r_e\sigma_v$, then Eq. (10) becomes

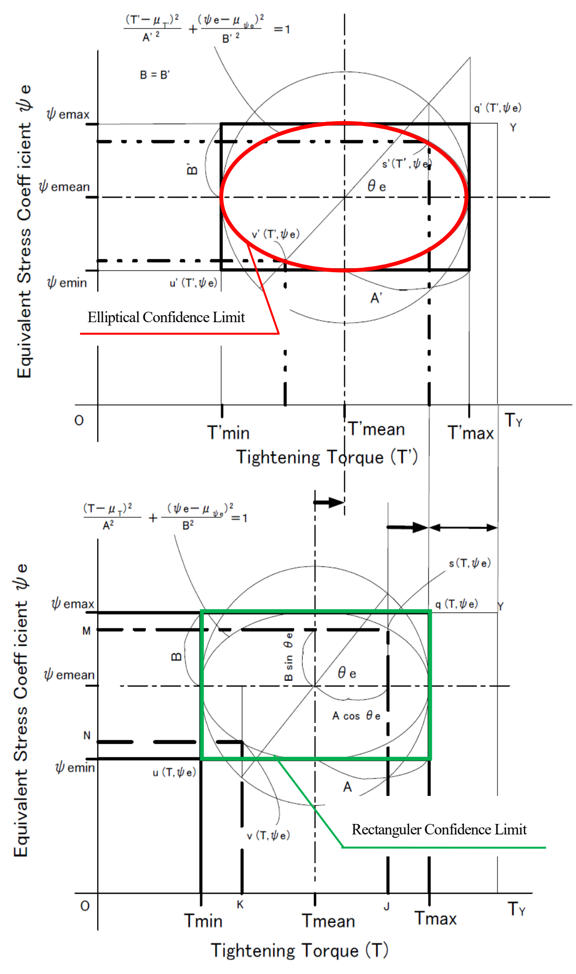



**Fig. 3:** Elliptical confidence limit for equivalent stress [1]

$$\frac{(T-\mu_T)^2}{A^2}+\frac{(\phi_e-\mu_{\phi e})^2}{B^2}=1 \ ,\cdots(14)$$

where $A=r_e\sigma_T$ and $B=r_e\sigma_{\phi e}$.

$r_e$ is the (substituted) random variable that corresponds to a cumulative percentage of a normal distribution when expressing the equivalent stress $\sigma_e$ in terms of $\mu_v$ and $\sigma_v$ (90% confidence limit $r_e$=1.645). The elliptical confidence limit given by Eq. (14) is shown in Fig. 3.

In Eq. (14), $\sigma_e$ is given by

$$\sigma_e=(\mu_T+A\cos\theta)(\mu_{\phi e}+B\sin\theta)/(A_s\cdot d).\cdots(15)$$

Finally, the maximum and minimum equivalent stress $\sigma_e'$ can be obtained from by Eqs. (16) and (17), respectively, which are based on Eq. (15).

$$\sigma'_{e\max}=(1+a\cdot\cos\theta_e)\{(\phi_{e\max}+\phi_{e\min})+(\phi_{e\max}-\phi_{e\min})\sin\theta_e\}\frac{T_{mean}}{2A_sd}\cdots(16)$$

$$\sigma'_{e\min}=(1-a\cdot\cos\theta_e)\{(\phi_{e\max}+\phi_{e\min})-(\phi_{e\max}-\phi_{e\min})\sin\theta_e\}\frac{T_{mean}}{2A_sd}\cdots(17)$$

Now, $\sigma'_{emax}$ is equal to the value at $s(T, \phi_e)$ in Fig. 3, which is lower than the value at point $q(T, \phi_e)$, at which the maximum is obtained by the conventional method. The position of $s(T, \phi_e)$ is lower than that of $q(T, \phi_e)$. Therefore, the value at point $s$ has a margin at the yield point and can be pulled up to the position of point $q$, as shown in Fig. 3, using the elliptical confidence limit.

If it is desired to express the relation between the maximum $\sigma'_{emax}$ of the equivalent stress and the lower limit $\sigma_{ymin}$ in a similar manner to Eq. (12) for the conventional method, it can be expressed by Eq. (18), in which $c'$ is the true initial equivalent stress ratio corresponding to $c$ in Eq. (12).

$$\sigma'_{e\max}=c'_{\max}\sigma_{y\min}\quad\cdots\cdots\quad(18)$$

The new proposed target value $T'_{mean}$ of the tightening torque is expressed by Eq. (19), which can be obtained by solving Eqs. (16) and (18).

$$T'_{mean}=\frac{2c'_{\max}\sigma_{y\min}\cdot A_sd}{(1+a\cdot\cos\theta_e)\{(\phi_{e\max}+\phi_{e\min})+(\phi_{e\max}-\phi_{e\min})\sin\theta_e\}}\cdots(19)$$

Thus, the main purpose of this paper is to show that the data is distributed in the ellipse shown in the upper figure of Fig. 3. That is rather than the rectangle in the lower figure of Fig. 3.

The ratios of each stress to the lower limit of the yield point are obtained as

$$\left.\begin{array}{l} R_S=\sigma/\sigma_{y\min}\\ R_T=\tau/\sigma_{y\min}\\ R_e=\sigma_e/\sigma_{y\min}\end{array}\right\}\cdots\cdots(20)$$

## TIGHTENING-TEST EQUIPMENT

In our experiment, the axial tension and torsional torque were measured by the data detector shown in Fig. 4. Figure 5 shows the test setup. In the case that every test bolt is attached to the strain gauge, attaching and measuring the work will take a long time; thus, the test was conducted using the test bracket for the data detector employed to measure axial tension $P'$ and torsional torque $Ts'$. In the preliminary test, the axial tension and torsional torque between the bolt and detector were observed to have the same value by using the attached strain gauges as shown in Fig. 6. Therefore, the following relations normally apply:

$$P=P',\quad Ts=Ts'.\cdots\cdots(21)$$

## CONDITIONS IN TEST BY DESIGN OF EXPERIMENTS METHOD

The experimental tightening test was conducted by the design of experiments (DOE) method using the parameters shown in Table 1. DOE is well known as an effective method for measuring and analyzing experimental data. The test was conducted using M12 and M16 high-strength bolts. The values of the target tightening torque and the tools in the test are shown in Table 2. The tightening work coefficient $a$ was set to 0.2 in this experiment and the target tightening torque was presumed to vary by ±20% in accordance with our previous paper [2]. Three workers conducted the tightening and the results were analyzed as randomized blocks.

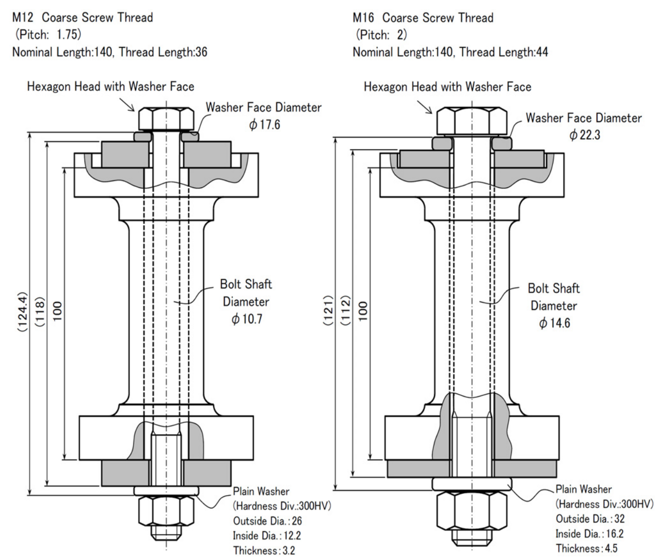



**Fig. 4:** Data detector used to obtain tightening characteristics

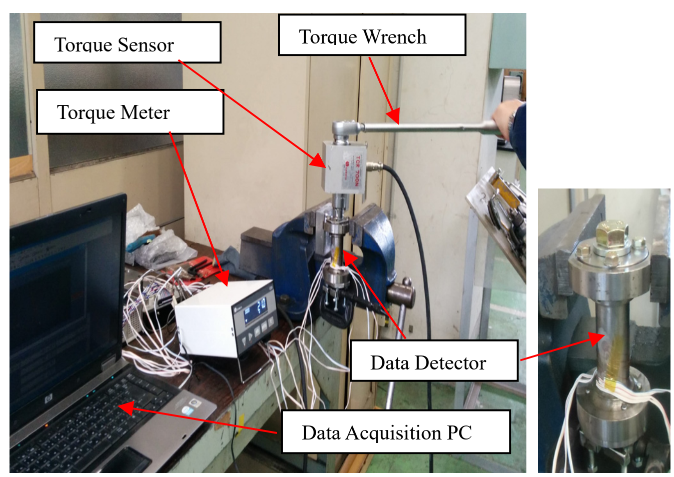



**Fig. 5:** Test setup for tightening test on bolted joint

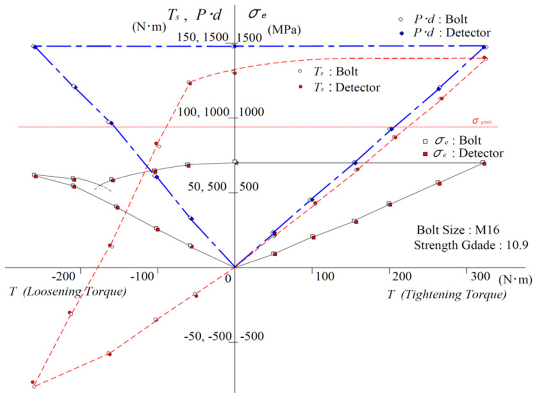



**Fig. 6:** Comparison between tightening characteristics of bolt shaft gauges and detector gauges

**Table 1:** Orthogonal Latin squares $L_8(2^7)$ (factors and levels) and linear graph

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 2 | 2 | 2 | 2 |
| 3 | 1 | 2 | 2 | 1 | 1 | 2 | 2 |
| 4 | 1 | 2 | 2 | 2 | 2 | 1 | 1 |
| 5 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| 6 | 2 | 1 | 2 | 2 | 1 | 2 | 1 |
| 7 | 2 | 2 | 1 | 1 | 2 | 2 | 1 |
| 8 | 2 | 2 | 1 | 2 | 1 | 1 | 2 |
| Factors | a | b | ab | c | ac | e | d |
| | Lubrication | Wrench | interac-tion | Strength Grade | interac-tion | Error | Bolt Size |
| | 1: Dry | 1: Preset type | | 1: 8.8 | | | 1: M12 |
| | 2: Loctite 263 | 2 :Dial Type | | 2: 10.9 | | | 2: M16 |

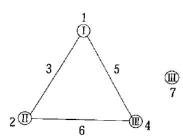



**Table 2:** Target tightening torque and tool (wrenches)

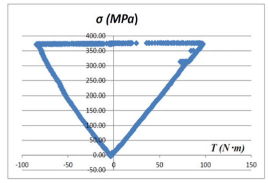
Tightening work coefficient $a$=0.2

| Bolt Specification | M12 with Colored Chromate Coatings | | | | M16 with Colored Chromate Coatings | | | |
|---|---|---|---|---|---|---|---|---|
| Strength Grade | 8.8 | | 10.9 | | 8.8 | | 10.9 | |
| Lubrication | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet |
| Tightening Torque (N·m) Theoretical Target Torque [2] | 85.1 | 68.9 | 124.6 | 101.2 | 213.7 | 172.2 | 313.8 | 252.0 |
| Indicated Torque for Worker | 86 | 68 | 124 | 102 | 214 | 172 | 314 | 252 |
| Tightening Tool (Wrench) Pre-set Type Wrench Asahi Tool Co.,Ltd. | LQK 280N (40–280 N·m) | | | | LQK 420N (60–420 N·m) | | | |
| Tightening Tool (Wrench) Dial Type Wrench Kyoto Tool Co.,Ltd. | CMD 143 (30–140 N·m) | | | | CMD 484 (100–480 N·m) | | | |

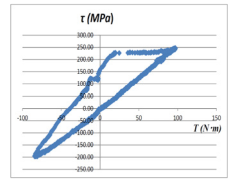
Dry : Use no Lubricant
Wet : Use Loctite 263 for Screw Thread Flank

## OBSERVATION OF PROCESS FROM TIGHTENING TO LOOSENING

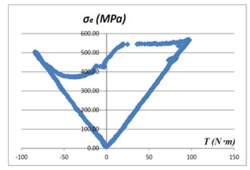
The tightening test involved a series of operations from the start of tightening to the completion of loosening. Figure 7 shows the tightening characteristics for axial stress $\sigma$, shear stress $\tau$, equivalent stress $\sigma e$, equivalent stress coefficient $\psi e$, torque coefficient (nut factor) $K$, torque ration$\eta$, coefficient of friction between screw flanks $\mu s$ and coefficient of friction at the bearing surface $\mu w$. The coefficient of friction, $\mu s$, $\mu_W$, and $\mu$ takes positive value in process of tightening, however it takes negative value in process of loosening from the Eq. [7].



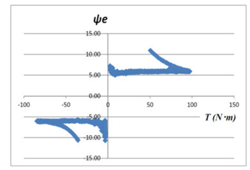

a) Axial stress



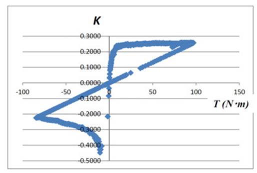

b) Shear stress



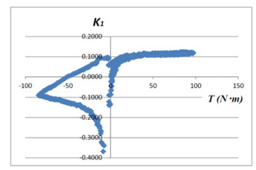

c) Equivalent stress



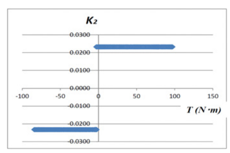

d) Equivalent stress coefficient



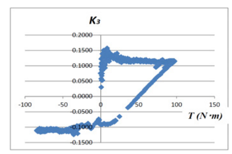

e) Torque coefficient (nut factor)



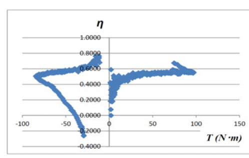

f ) Torque coefficient between screw flanks



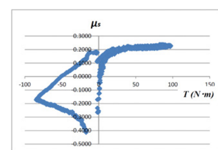

g) Axial-tension torque torque coefficient



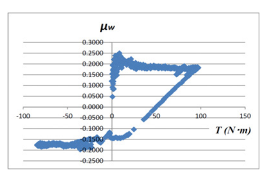

h) Bearing-surface torque coefficient



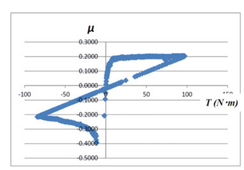

h) Torsion torque ratio




i) Coefficient of friction between screw flanks




j) Coefficient of friction at bearing surface




k) Coefficient of friction ($\mu$=$\mu_s$=$\mu_W$)

**Fig. 7:** Observation of the tightening characteristics in tightening and loosening processes

## VERIFICATION OF ELLIPTICAL CONFIDENCE LIMIT METHOD

The main purpose of this experimental study is to verify the elliptical confidence limit method. Figure 8 shows the equivalent stress coefficient plotted as a 95% confidence limit ellipse (solid line) and a 99% confidence limit ellipse (dotted line) obtained in the experimental study. Almost all the data lie within the 95% elliptical confidence limit.

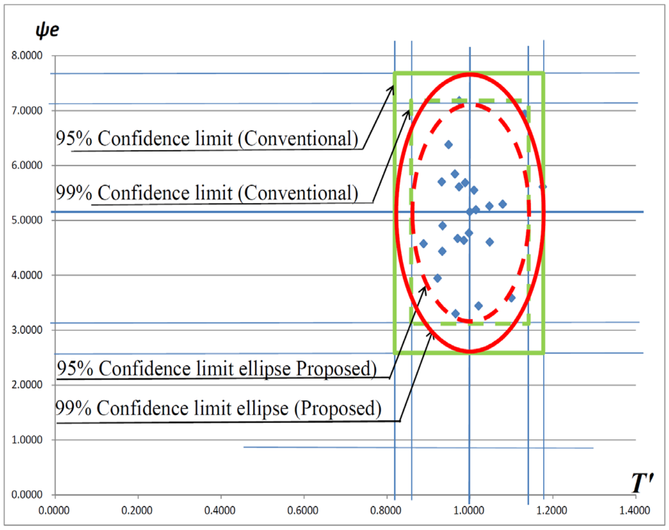



**Fig. 8:** Results for equivalent stress coefficient plotted in confidence limit ellipse

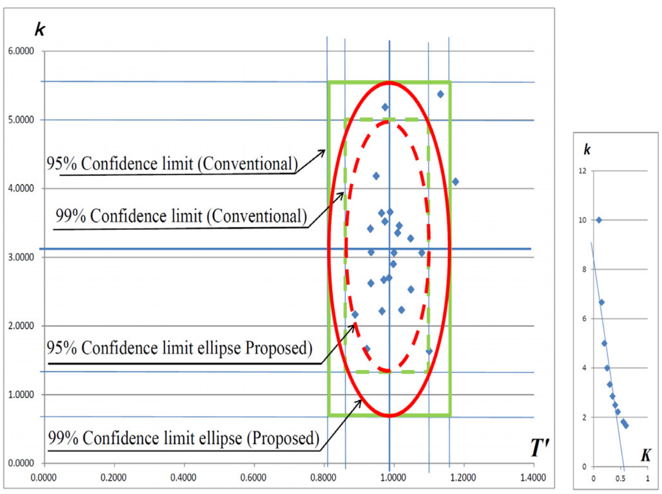



**Fig. 9:** Results for axial tension factor plotted in confidence limit ellipse and relation between ***k*** and ***K*** (0.1-0.6)

Several points are outside the 95% confidence limit ellipse. This is considered to be due to the overtightening and a large distribution of the torque coefficient in these cases. In this test, the average tightening torque is 8% larger than the target value given later in Table 4. Nevertheless, the validity of the elliptical confidence limit method has been verified practically. Even though this experiment was performed by hand tightening, which generally results in a large variation of data, the validity of the method was shown. Naturally, further experiments and research are necessary for validation of this method theoretically and experimentally.

On the other hand, the initial axial tension and axial stress are also distributed within an elliptical confidence limit similarly to the equivalent stress. When the axial tension factor is expressed as $k$ ($k$=1/$K$), the relation between the tightening torque and the axial tension (stress) is determined as

$$P=\sigma As=T/(\mathrm{K}d)=kT/d. \quad \cdots\cdots \quad (22)$$

Normally, the torque factor $K$ is approximately between 0.1 and 0.6. Thus, the relation between $k$ and $K$ can be expressed by the following linear equation:

$$k=aK+b=(-13.67K+8.59)\ .\cdots\cdots \quad (23)$$

Figure 9 shows the results for the axial tension factor which plotted in a confidence limit ellipse based on Eq. (14). That is similarly to the case of the equivalent stress coefficient (Fig. 8).

Also, the maximum axial stress and minimum axial stress are obtained as follows, similarly to Eqs. (16) and (17) for the equivalent stress.

$$\sigma_{\max}=(1+a\cdot\cos\theta_P)\{(k_{\max}+k_{\min})+(k_{\max}-k_{\min})\sin\theta_P\}\frac{\mathrm{T}'_{\mathrm{mean}}}{2\mathrm{A_s d}} \cdots (24)$$

$$\sigma_{\min}=(1+\mathrm{a}\ \cdot\cos\theta_P)\{(k_{\max}+k_{\min})-(k_{\max}-k_{\min})\sin\theta_P\}\frac{\mathrm{T}'_{\mathrm{mean}}}{2\mathrm{A_s d}} \cdots (25)$$

Almost all the data are plotted in the confidence limit ellipse. The validity of the elliptical confidence limit method is also therefore verified in the case of axial stress (Axial tension).

Figure 10-12 show frequency diagrams for equivalent stress coefficient $\psi$e, axial tension factor $k$, and torque coefficient $K$ in overall data. Those diagrams are analyzed for skewness and kurtosis ratio. The results of analysis are not so good for normalized (Gauss) distribution, however in detail, these analyses will be described in our next paper.

## ANALYSIS OF THE TIGHTENING CHARACTERISTICS OF BOLTED JOINTS

The tightening characteristics obtained by analysis are shown in Table 3. The values were obtained not from the orthogonal Latin squares shown in Table 1 but from all test results. The average and the 95% and 99% confidence limits are shown. Table 4 shows the analysis results of the overtightening torque ratio, normalized tightening torque, loosening torque ratio, and the relative decreases in the axial stress, shear stress, and equivalent stress.

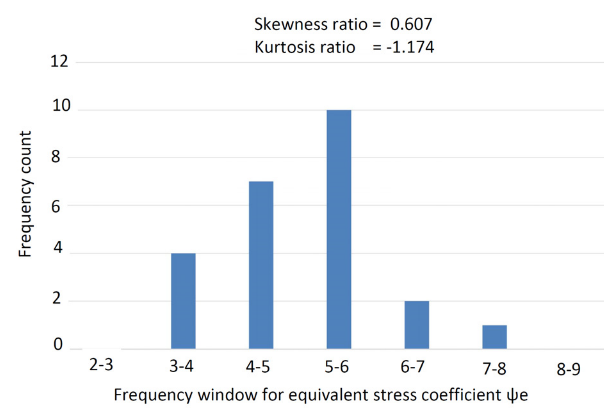



**Fig. 10**: Frequency diagram of equivalent stress coefficient

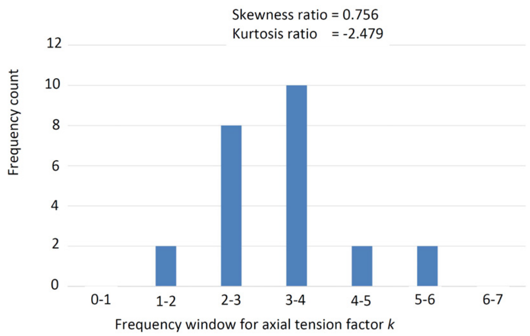



**Fig. 11**: Frequency diagram of axial tension factor

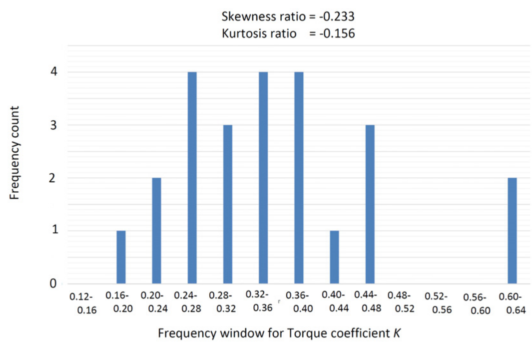



**Fig. 12**: Frequency diagram of torque coefficient (Nut factor)

**Table 3:** Analysis results for tightening characteristics (overall)

| Characteristics / Statistical Value | Equivalent Stress Coefficient $\psi e$ | Axial Tension Factor $k$ | Torque Coefficient (Nut Factor) $K$ | Torque Ratio $\eta$ | Coefficient of Friction at Screw Flank $\mu s$ | Coefficient of Friction at Bearing Surface $\mu w$ | Coefficient of Friction $\mu(\mu_s=\mu_w)$ |
|---|---|---|---|---|---|---|---|
| Average | 5.096 | 3.156 | 0.350 | 0.504 | 0.276 | 0.289 | 0.283 |
| 95% Confidence Limit max | 7.035 | 4.996 | 0.562 | 0.661 | 0.419 | 0.535 | 0.467 |
| 95% Confidence Limit min | 3.156 | 1.316 | 0.139 | 0.347 | 0.132 | 0.043 | 0.099 |
| 99% Confidence Limit max | 7.649 | 5.578 | 0.628 | 0.711 | 0.465 | 0.613 | 0.526 |
| 99% Confidence Limit min | 2.543 | 0.734 | 0.072 | 0.297 | 0.087 | -0.035 | 0.041 |

**Table 4:** Torque and stress behavior

| Characteristics / Statistical Value | Over-tightening Ratio $T_R$ | Normalized Tightening Torque $T_N$ | Loosening Torque Ratio $D_L$ | Decrease in Axial Stress (Tension) $D_S$ | Decrease in Shear Stress $D_T$ (Torsion Torque) | Decrease in Equivalent Stress $D_e$ |
|---|---|---|---|---|---|---|
| Average | 1.080 | 1.000 | 0.894 | 1.020 | 0.701 | 0.844 |
| 95% Confidence Limit max | 1.227 | 1.122 | 1.037 | 1.080 | 1.049 | 0.998 |
| 95% Confidence Limit min | 0.934 | 0.878 | 0.752 | 0.960 | 0.354 | 0.689 |
| 99% Confidence Limit max | 1.273 | 1.161 | 1.082 | 1.114 | 1.158 | 1.046 |
| 99% Confidence Limit min | 0.888 | 0.839 | 0.707 | 0.926 | 0.244 | 0.641 |

$T_R$: overtightening ratio
=tightening torque measured by torque sensor/target torque
$T_N$: normalized tightening torque
= overtightening ratio/average overtightening ratio
$D_L$: loosening torque ratio
=maximum loosening torque/maximum tightening torque
$D_S$: decrease in axial stress (tension) ratio
=maximum axial stress/axial stress at torque wrench release
$D_T$: decrease in shear stress (torsional torque) ratio
= maximum shear stress/shear stress at torque wrench release
$D_e$: decrease in equivalent stress ratio
=maximum equivalent stress/equivalent stress at torque wrench release

These results are summarized as follows.

(1) For the torque wrenches used in this study, the actual maximum tightening torque was on average 8% larger than the target tightening torque.

(2) From the normalized tightening torque, the tightening coefficient $\boldsymbol{a}$ (Eq.(19)) was 0.122 at the 95% confidence limit and 0.161 at the 99% confidence limit of the range in this study.

(3) The loosening torque was 80% of the tightening torque in theory but was 89.4% on average in this study.

(4) The axial stress (axial tension) during the torque wrench release remained close to the maximum value at the time of tightening.

(5) The average shear stress was about 70% of the maximum value during tightening during the torque wrench release.

(6) The average equivalent stress was about 85% of the maximum value at the time of tightening during the torque wrench release. This result can be used to study the acceptance margin of an external force.

Following the results of this analysis, the characteristic values in screw tightening were experimentally analyzed. Table 5 shows the results of analyzing the variance of the equivalent stress coefficient. For tightening standardization, such analysis is necessary for various types of screws and tools. As shown in this table, statistical analysis was used to analyze the data obtained in experiments. However, also these analysis results will be described in detail in our next paper.

**Table 5**: Variance of equivalent stress coefficient $\phi e$

a) Data ( $\phi e$)

| | Tightening Worker A | Tightening Worker B | Tightening Worker C |
|---|---|---|---|
| 1 | 7.179 | 5.614 | 6.816 |
| 2 | 5.552 | 4.605 | 5.296 |
| 3 | 4.864 | 4.672 | 4.769 |
| 4 | 4.575 | 3.947 | 3.589 |
| 5 | 5.704 | 5.686 | 5.195 |
| 6 | 3.300 | 3.444 | 5.612 |
| 7 | 4.903 | 6.379 | 5.846 |
| 8 | 4.636 | 5.156 | 4.437 |

b) Estimate of population mean

| Factor | Level | Average | Confidence Limit 99% min | Confidence Limit 99% max | Confidence Limit 95% min | Confidence Limit 95% max |
|---|---|---|---|---|---|---|
| A: Lubrication | 1: Dry | 5.1232 | 4.5241 | 5.7223 | 4.6899 | 5.5565 |
| | 2: Loctite 263 | 5.0248 | 4.4257 | 5.6239 | 4.5914 | 5.4581 |
| B: Torque Wrench Type | 1: Preset | 5.3336 | 4.7345 | 5.9327 | 4.9002 | 5.7669 |
| | 2: Dial | 4.8144 | 4.2153 | 5.4135 | 4.3811 | 5.2477 |
| C: Strength Grade | 1: 8.8 | 5.6356 | 5.0365 | 6.2347 | 5.2022 | 6.0689 |
| | 2: 10.9 | 4.5124 | 3.9133 | 5.1115 | 4.0791 | 4.9457 |
| D: Screw Size | 1: M12 | 5.1004 | 4.5013 | 5.6995 | 4.6670 | 5.5337 |
| | 2: M16 | 5.0476 | 4.4485 | 5.6467 | 4.6143 | 5.4809 |

c) Analysis of Variance table

| Factor | Sum of Squares | Degree of Freedom | Unbiased Estimate of Variance | Ratio of Variance | P Value | Ratio of Contribution | Judgment |
|---|---|---|---|---|---|---|---|
| Block(*R) | 0.2669 | 2 | 0.1335 | 0.2691 | 0.7677 | 0.0000 | |
| A | 0.0581 | 1 | 0.0581 | 0.1172 | 0.7369 | 0.0000 | |
| B | 1.6172 | 1 | 1.6172 | 3.2604 | 0.0911 | 5.0753 | |
| C | 7.5694 | 1 | 7.5694 | 15.2607 | 0.0014 | 32.0191 | ** |
| D | 0.0167 | 1 | 0.0167 | 0.0337 | 0.8568 | 0.0000 | |
| AB | 5.0976 | 1 | 5.0976 | 10.2773 | 0.0059 | 20.8300 | ** |
| AC | 0.0251 | 1 | 0.0251 | 0.0507 | 0.8250 | 0.0000 | |
| Error | 7.4401 | 15 | 0.4960 | | | 42.0756 | |
| Unconformity | 0.4518 | 1 | 0.4518 | 0.9052 | 0.3575 | | |
| Pure Error | 6.9882 | 14 | 0.4992 | | | | |
| Total | 22.0911 | 23 | | | | 100 | |

## CONCLUSIONS

It is important to provide high initial axial tension to ensure tightening reliability and prevent self-loosening and fatigue breakage. In our previous study, the statistical distribution of the magnitude of the combined stress (equivalent stress) was formulated and proposed using shear strain energy theory, the torque coefficient (friction coefficient), and the equivalent stress coefficient for a bolted joint tightened by the calibrated wrench method.

In this study, the main purpose was to verify the validity of the elliptical confidence limit method.

The conclusions of this study are as follows.

(1) The experimentally obtained results for the equivalent stress coefficient were plotted in 95% and 99% confidence limit ellipses. Almost all the data were plotted in the 95% confidence limit ellipse. Therefore, the validity of the elliptical confidence limit method was verified practically under the experimental conditions in this study.

(2) The initial axial tension and axial stress were also distributed within an elliptical confidence limit similarly to the equivalent stress. Almost all the data were plotted in the confidence limit ellipse. The elliptical confidence limit method was thus also validated for the case of axial stress (axial tension).

(3) Furthermore, the bolted-joint screw-thread characteristics (torque coefficient, equivalent stress coefficient, coefficient of friction, etc.) in the tightening process should be clarified by an experimental approach and observation.

**ACKNOWLEDGMENTS**

We would not have been able to perform this research without the previous results of many researchers and engineers, who provided various helpful suggestions. We thank the pioneering researchers from the bottom of our hearts.

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