

Real-time Bolt Axial Force Fastening System Using Ultrasonic Waves in Mass Production Assembly Process

Kazuhiro TSUZAKI¹Toshitsugu SAKAKIBARA¹Yasushi HARA²Tsukasa ISHIDA²

ABSTRACT

In order to reduce variations in fastening force in mass production assembly processes, a real-time bolt axial force fastening system was developed to provide fastening force that is stable, whether the work is done by automated equipment or by humans. An ultrasonic wave method is used to measure axial force, with a gap between the bolt head and the probe for increased accuracy. Bolts used for measurement were bolts with specifications that allow for forming by existing manufacturing processes. The probe emits an ultrasonic beam that is propagated by means of a newly developed solid propagation medium and receives echoes separately from the head and bottom of the bolt. Operations on the two received echoes are carried out simultaneously so that measurements are stable even while fastening is underway, realizing real-time axial force measurement. As a result, measurement of axial force during fastening is realized without changing production takt time, bolt manufacturing costs, and other such existing conditions.

This technology is capable of bidirectional communication with nutrunners, the electric fastening equipment that has been widely adopted for mass production fastening processes. It can control fastening force to a preset axial force value, and it has successfully reduced axial force variations to one-tenth or less than what is experienced with existing torque methods of tightening.

1. Introduction

Demands from society for decarbonization in recent years have accelerated the electrification of the automobile. In electrified vehicles, the battery unit is ordinarily fastened to the floor with bolts. For this reason, there is a demand for being able to control the fastening axial force during manufacturing so that loosening and fatigue do not occur in the fastening portion due to bolt expansion from heat generated by the battery, stress in the axial direction from road load, or other such reasons. There are many other, similar fastening axial force control processes in automobile manufacturing, so the need for highly accurate axial force control is only ever increasing.

The current axial force measurement methods include the ultrasonic wave method for measuring stretching of the bolt shaft, the strain gauge method, the electromagnetic field method⁽¹⁾, and so on. Axial force measurement during the mass production assembly process is subject

to time constraints. For this reason, there is demand for tightening with sockets with the simultaneous use of measurement sensors. As shown in Table 1, however, the electromagnetic field method cannot readily be used simultaneously for structural reasons. The other methods cannot readily be used, either, for reasons related to layout constraints during measurement, the need for bolt machining and sensor attachment with glue, and the need for judgment of measurement results.

Due to these factors, the torque method has generally been used instead on the mass production line. The torque method, however, is affected by the coefficient of friction, the area of contact, and other such influences based on individual differences that are specific to the particular component. Therefore issues arose⁽²⁾ because axial force values are not stable and axial force variations of around $\pm 30\%$ normally occur. Consequently, designs are required to be capable of maintaining sufficient axial force even at lower limit values, but when the objects being fastened

¹ Honda Motor Co., Ltd.

E-mail: kazuhiro_tsuzaki@jp.honda

² RYODEN SHONAN ELECTRONICS CORPORATION

Table 1 Challenges of axial force measurement methods in mass production assembly

	Measurement during fastening	Layout constraints	Bolt machining	Human judgment
Ultrasonic wave method	Available (Good)	None (Good)	Surface only	Needed
Strain gauge method	Available (Good)	Wiring process (Not good)	Machining and gluing	Needed
Electromagnetic field method	Not available (Not good)	Sensor size (Not good)	Not needed (Good)	Needed

are large, the fact that the space and mass necessary for fastening increase becomes an issue.

The aim, therefore, is to realize real-time axial force fastening of bolts in the mass production process without complicating the process, without necessitating bolts to be processed for special measurement use, and without involving judgment of measurement results, as the strain gauge method and electromagnetic field method do. An ultrasonic wave method that is thought to offer the possibility of realizing axial force fastening without those complications and so on was developed. The development goal was not to affect the tightening socket layout, takt time, and bolt costs that are conditions of current mass production. In addition, it was made a necessary condition that the method would not change existing processes and that by integrating a nutrunner and an ultrasonic wave axial force meter, it would be made capable of simultaneously fastening a bolt and controlling the axial force.

2. Principles and Issues of Axial Force Measurement by Ultrasonic Wave

2.1. Principles of Axial Force Measurement by the Ultrasonic Wave Method

Axial force is the force of a bolt shaft that has been stretched by tightening trying to return to its original state. The axial force can be grasped by measuring the amount of stretching in terms of bolt length change. The amount of stretching and the change in propagation time of an ultrasonic wave passing through the bolt are in a proportional relationship, so measurement by ultrasonic wave uses the difference in propagation time before and after tightening in place of the amount of stretching.

Figure 1 shows the basic principle of axial force measurement by ultrasonic waves.

First the probe is put in close contact with the head of a no-load bolt, an ultrasonic beam is generated, and the propagation time (t_1) in microseconds (μs) until the bottom echo has been received is recorded. Measurement is also made after tightening, and when that propagation time (t_2 in μs) is acquired, the difference in propagation time from before tightening is calculated. The propagation time can

be converted into length of (x) mm by multiplying it by the material-specific sound velocity. By multiplying this value with the spring constant (k) in N/mm of the bolt, the axial force value (F) in kN is calculated.

The calculation of the axial force value is expressed as in Eq. (1).

$$F = k (x_2 - x_1) \quad (1)$$

2.2. Method of Setting the Measurement Reference Point

The reference point for measurement is acquired by setting a gate for echoes from the several wave lengths acquired. Gate refers to the time position and section of waves that are monitored, together with their height level. In order to compensate for attenuation due to the time direction movement of the echo that accompanies tightening of the bolt, the change in measured length, and other such factors, the position that is set is ordinarily placed in a broad section with a width of about three wave lengths from the first wave, and lower than the peak position of the waveform.

For setting the measurement reference point, the zero cross method that involves less influence from waveform change is commonly used⁽³⁾. The zero cross method is a method that sets the reference point at the zero-cross point, which is where a wavelength of height exceeding the gate position first intersects with the zero baseline. Figure 2 shows the method of setting the reference point.

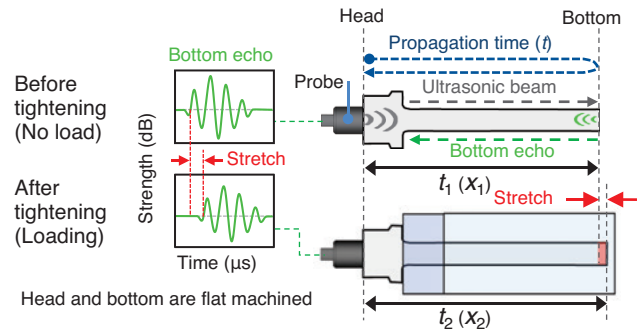


Fig. 1 Principle of axial force measurement by ultrasonic waves

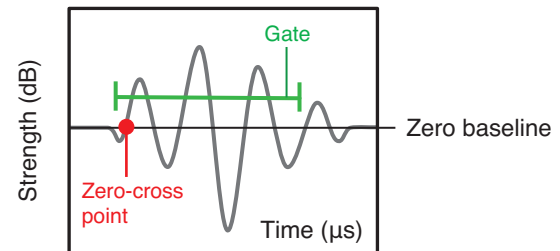


Fig. 2 Reference point setting method for echo

2.3. Issues of the Ultrasonic Wave Method

Measurement by ultrasonic wave is carried out with the probe placed closely against the bolt head surface at a constant pressure. However, the echo from the head cannot be distinguished when the distance from the head is so small, so measurement is not of the pure bolt length, but rather of the distance (T-B1) between the transducer (T) built into the probe and the bottom echo (B1).

Figure 3 shows an overview of the probe structure and bolt contact.

Piezoelectric ceramic (PZT) is ordinarily used for the transducer, which is covered by a protective plate layer⁽⁴⁾,⁽⁵⁾. Ultrasonic waves emitted by the transducer pass through the protective plate and the flexible layer of propagation medium and propagated to the bolt. At this time, if the applied load of the probe and its mounting position are changed, the thickness of the flexible layer will change and the measurement distance will be affected.

A high degree of shape accuracy in terms of bolt flatness, squareness, surface roughness, and so on is sought as a way to address this⁽⁶⁾. For that reason, it was necessary for the bolts used for ultrasonic wave measurement to be machined by high-precision cutting.

In addition, if air is present between the probe and the measurement surface, then the sudden change in the acoustical impedance characteristics will cause attenuation of the ultrasonic wave, resulting in measurement malfunction⁽⁷⁾. In order for there not to be a layer of air, a flexible propagation medium is necessary. A liquid propagation medium that can fill the space all the way to a minute layer of air is therefore used. However, a liquid coating process cannot readily be added to the existing mass production assembly process because it would impose additional takt time and costs.

Furthermore, even when the probe position and bolt shape accuracy have been secured, the application of axial force may result in stress inside the bolt, and the influence of distortion may change the acoustical characteristics⁽⁸⁾ so that echo output and time position are no longer stable. Figure 4 shows a typical example of such change. As this indicates, when tightening reduces the echo output from the first wave, that wave misses the gate so that the zero-cross point is moved to the second wave. This resulted in the issue of the measurement distance ending up being displaced

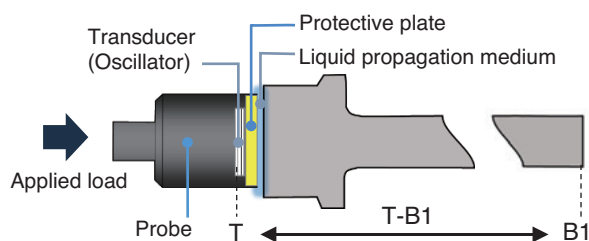


Fig. 3 Overview of probe structure and bolt contact

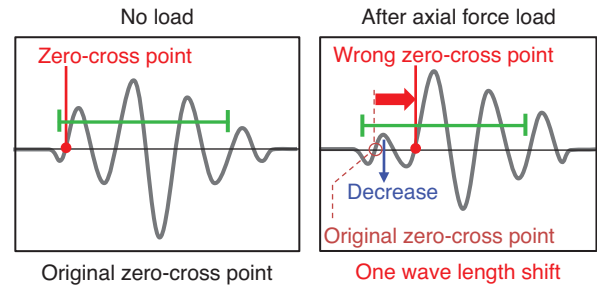


Fig. 4 Effect of changes in echo output on measurements

by one wave length. When the measurement reference is displaced in this way, it can lead to mismeasurement. For this reason, it was necessary for the person performing measurement to make corrections by checking and adjusting the gate position, and so on.

3. Overview of Real-time Axial Force Fastening System Using Ultrasonic Wave

In order to reduce variations in fastening force during the mass production assembly process, a real-time axial force fastening system that operates by ultrasonic waves was developed. Figure 5 shows the basic system configuration.

An ultrasonic wave axial force meter was integrated with the nutrunner used for tightening in order to incorporate coordinated control by intercommunication.

The probe for axial force measurement is held inside the interchangeable tightening socket at the tip of the nutrunner, where it is retained by a spring. When the probe touches the bolt head, it is in close contact with it and instantly measures the bolt length. The probe is electrically connected with the ultrasonic wave axial force meter through a slip ring, and it sends the nutrunner a signal to begin fastening.

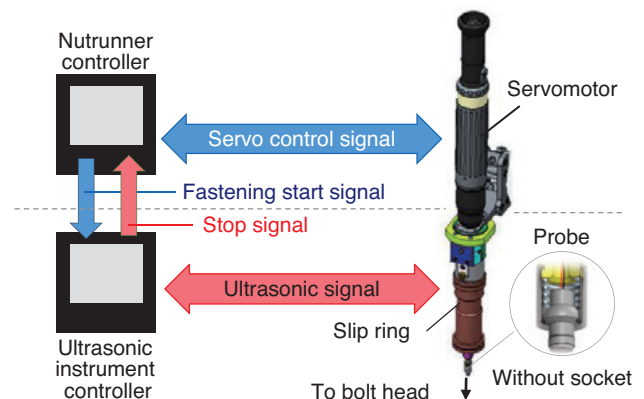


Fig. 5 Basic system configuration

The bolt length is measured in real-time, even while fastening is underway, and that length is converted in an axial force value. When the specified axial force is reached, the fastening force is controlled and stopped.

A method of measurement that is not influenced by the probe position or bolt shape accuracy was developed. A gap was set between the probe and the bolt so that, in addition to the bolt bottom echo, the new head surface echo (S) could also be measured.

In this way, a measurement method was devised that would be able to obtain the pure bolt length regardless of the probe position.

The issue of zero-cross point shift was also addressed by a program that continues to track the point even when the waveform changes.

For the propagation medium, the liquid was replaced with a flexible elastomer material. This made repeated reuse possible and made the liquid application process unnecessary. In addition, by putting this in an integrated structure with a high hardness resin material, a non-deforming portion was added and the state when mounted against the bolt was stabilized.

4. New Measurement Method and Technology Applied

4.1. Measurement Method for Application to Mass Production Process

4.1.1. Effectiveness of measurement method with gap set

In the mass production fastening process, there are factors such as automated equipment and differences in human skill that can cause the probe position to vary. As a measurement method that would not be influenced by these factors, the S-B1 measurement method that recesses a part of the bolt head and simultaneously measures the head and bottom echoes was developed⁽⁹⁾. Figure 6 shows the gap

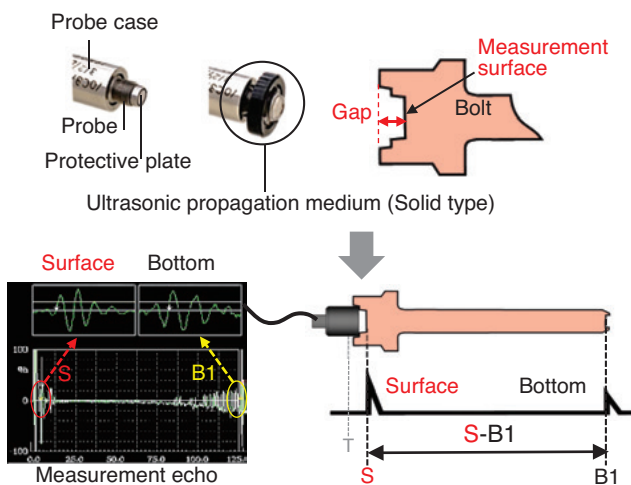


Fig. 6 Gap structure and measurement method

structure and measurement method.

By this means, it became possible to grasp the relative time difference in echoes from both ends of a bolt in real-time, and to measure the pure bolt length regardless of the probe position.

As a result, it became possible to determine the change in bolt length accurately without being affected by work skill levels and so on. The issues with probe position and component accuracy were also addressed. Moreover, since existing methods involved placing the probe vibrating surface in contact with metal bolts, this sometimes led to cracking of the transducer. As a result of adopting the S-B1 method, it became possible to help avoid direct contact with rigid objects.

4.1.2. Measurement reference point anti-displacement function

An auto-tracking function was developed that automatically tracks waveform changes when measuring axial force. With conventional measurement methods, the operator would visually inspect the waveform. If a change in the zero-cross point was seen, the operator would make manual corrections by adjusting the waveform gain or the gate position, and so on. The same function is already in use with ultrasonic wave flaw detection, where the method used was to cause the gate position to be tracked when the echo changed.

With axial force measurement, however, the amount of change in the bolt head differs from that in the shaft. A new two-gate tracking function was therefore developed to track the gate positions according to their respective amounts of change⁽¹⁰⁾.

Figure 7 shows the two-gate tracking system.

This function synchronizes with the ultrasonic wave pulses that are emitted at a high frequency of about 1 kHz and acquires the individual propagation time for each gate.

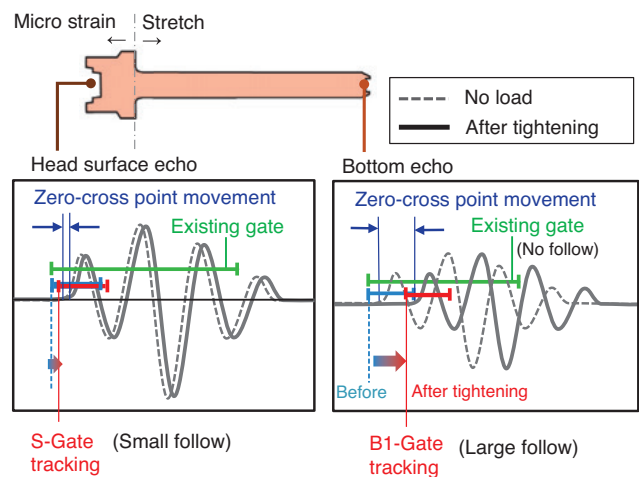


Fig. 7 Operational schematic diagram of newly developed two-gate tracking method

The difference from the previously acquired propagation time is calculated for each gate and the gate position is corrected. As a result, the gate position is also tracked with respect to the amount of change in the echo time position that occurs with bolt fastening. The gate can therefore be configured to be as narrow as the one wave length width that is necessary to set the zero-cross point. Consequently, the occurrence of mismeasurement factors is inhibited and the work of checking and correcting the measurement reference point was made unnecessary.

4.1.3. Fastening state stability judging function

When implementing fastening control by means of axial force values, the possibility for carrying out axial force fastening regardless of the operator's skill becomes necessary. Two-gate tracking and other such functions help reduce the burden on the operator, but there is a need for a function that can automatically detect irregularities in tightening and measurement and judge the fastening state.

A malfunction-detecting function that uses the frequency characteristics of acquired echoes was developed⁽¹¹⁾ as a method for judging the fastening state. This function is focused on changes that occur in the waveform shape as detected from the tilt of the probe, transducer wear, foreign substances, bolt irregularities, and other changes in peripheral conditions. A fast Fourier transform (FFT) was applied in advance to a malfunction waveform and the three items of center frequency, peak frequency, and fractional bandwidth⁽¹²⁾ were entered in a database. Then it automatically detects the presence or absence of malfunction by comparison with the measured waveform during tightening.

Figure 8 shows examples of FFT analysis for normal and malfunction states.

Malfunction detection is carried out from the time when the probe comes in contact with the bolt to when tightening is completed. When a malfunction is judged to have occurred, the system is set to control the nutrunner and stop it.

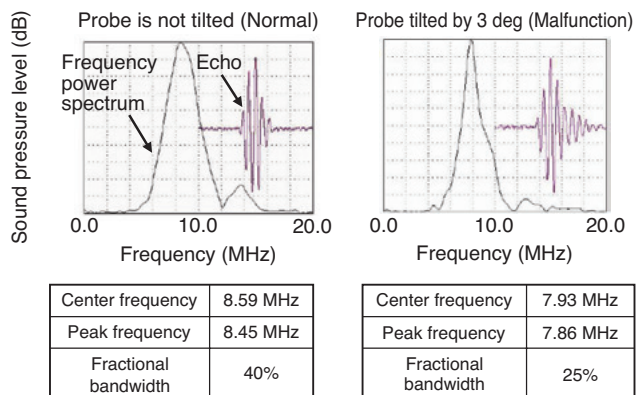


Fig. 8 Examples of normal and malfunction FFT analysis

4.2. Solid Ultrasonic Wave Propagation Medium for Application to Mass Production Process

In order not to enlarge the fastening work process, solid propagation medium was developed to use in place of a liquid. As shown by its shape in Fig. 9, this medium has a hybrid structure with an ultrasonic wave propagating part that uses a relatively soft elastomer material with a hardness of about 15⁽¹³⁾ and a fixed part that uses the high hardness resin material polypropylene (PP).

Since a characteristic of the elastomer material is that its shape can readily be changed, it is suited to filling the space between the probe and the bolt head. However, in prior checks using the elastomer on its own, after it had been repeatedly compressed by more than 50% some tens of times, cracking and plastic deformation occurred so there was a possibility that its functionality as a propagation medium could be impaired within a short time. Because it is a soft material, it could not readily be made to maintain a fixed shape, so the probe position ended up becoming unstable with respect to the bolt, and there were issues with the method of fixing the elastomer material itself in place. The issues were therefore addressed by making it a two-color molded part together with the PP material.

4.2.1. Method of fixing medium in place and effectiveness of probe position stabilization

As shown by the structure in Fig. 10, a screw-in style was adopted for the method of fixing in place. The PP part was shaped to an appropriate length as a female screw. By screwing it onto the probe tip, which was shaped as a male screw, the elastomer material and the vibrating surface are fixed in a position of contact. The PP part of the propagation

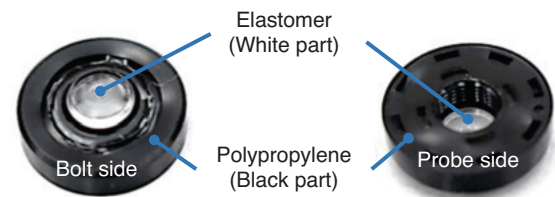


Fig. 9 Solid type ultrasonic propagation medium

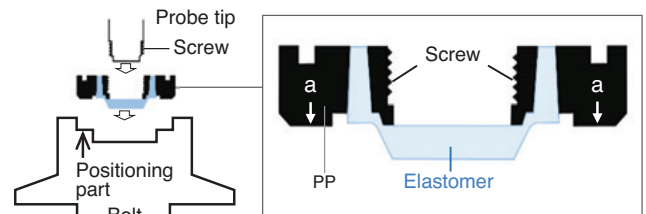


Fig. 10 Cross-section and peripheral layout of ultrasonic propagation medium

medium, which is fixed in place, fits together with the positioning part on the bolt side, which is in the first level of the recessed area, securing the stability of the probe position. The elastomer material part comes into contact with the measurement surface, which is in the second level of the recessed area, where it propagates ultrasonic waves. Making it detachable by means of the screw shape also gave consideration to its replaceability.

4.2.2. Durability of elastomer material

To secure the durability of the elastomer, the compression ratio of the elastomer is kept to 50% or less to control the amount of the material that projects from the bolt contact surface of PP material (surface a in Fig. 10). To confirm durability, it was tested by repeatedly compressing it against a bolt shape. The result was that a portion was observed to whiten after 150,000 compressions, but it retained normal measurement function in terms of its shape and propagation characteristics. Supposing a mass production process that involved 1,000 iterations of tightening work in one day, this confirms durability corresponding to a total of 150 days of tightening work. Figure 11 shows the state of the solid propagation medium after testing.

4.3. Anti-lifting Probe Structure for Application in Mass Production Process

During the fastening process, it is conceivable that the fastening equipment may become tilted due to work circumstances or other such external factors. When that happens, if a part of the probe lifts away from the bolt, the close contact will be disrupted and measurement malfunction could occur. As a measure against this, a spring is used in the part where the probe and the fastening

Number of samples: 48

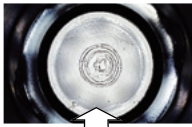
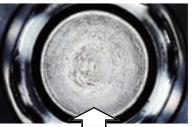
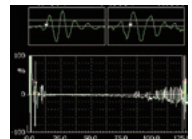
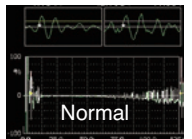
Number of compressions	0	150,000
Elastomer state	 × 200	 × 200
Change in outer diameter	(Standard ± 0.05)	-0.01 to +0.03
Change in thickness (mm)	(Standard ± 0.05)	-0.02 to +0.02
Measured echo		

Fig. 11 Results of repeated compression durability test

equipment are connected in a floating holding structure. This structure can keep the probe from being influenced by tilting of the equipment. As can be seen in Fig. 12, however, which shows a structure based on a general cylindrical probe shape, when the floating function was added using a general purpose probe, the structure ended up having a fulcrum at a location that is removed from the end of the bolt. Because of this, the range of probe movement from the bolt measurement surface was narrowed by about 1.5 deg, and this limited the response to tilting due to external factors.

In order to deal with large amounts of tilting, therefore, the probe structure was reviewed and another floating function was added at a location close to the bolt end.

The part that is in contact with the added spring was made spherical so as to secure an additional 5 deg for the range of movement in all directions. This secures flexible close contact by the probe against bumping or rattling of the fastening equipment or tilting resulting from human operation^{(14),(15)}.

Figure 13 shows the new floating holding structure.

4.4. Axial Force Measurement Bolt Applicable in Mass Production

In this development, the bolt head needed to have two functionalities that serve in measuring axial force and stabilizing the probe position. To support these, a mass production bolt was used as a base and a two-level recess was added to it.

With the layout of a general purpose probe, however,

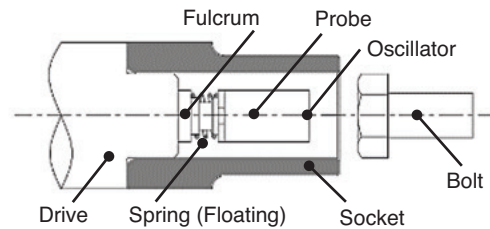


Fig. 12 General structure of probe in tool

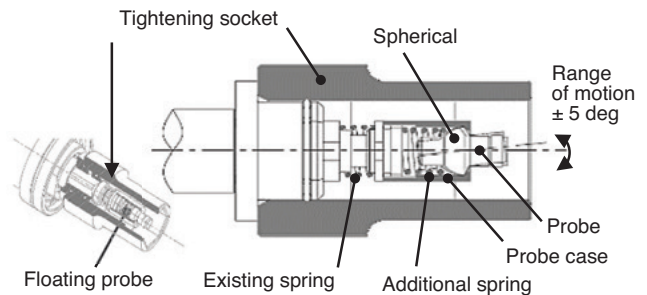


Fig. 13 New floating holding structure for probe

as shown by the shape in Fig. 14, a deep counterbored shape in the axial direction of the bolt becomes necessary. Therefore upset forging limitations^{(16), (17)} influence it during heading and the molding shape cannot readily be achieved. In the automotive components field, boron steel is commonly used for bolts of strength class 10.9 or lower^{(17), (18)}. Therefore the bolt head recess was shaped to maintain measurement accuracy even with boron steel⁽¹⁹⁾.

4.4.1. Optimization of molded shape

With deep counterbored shape molding, the flow of material cannot readily be tracked. As indicated by the comparison of molding analysis results shown in Fig. 15, areas appear where the mold has not contacted the steel material. This and other such issues with molding were found.

This was addressed by verifying the optimal shape using heading analysis (DEFORM ver. 11.1 from Yamanaka Eng Co., Ltd.) in a parametric study by bolt head shape. Based on the results, enlarging the recess diameter and making the measurement surface shallower produced a shape with uniform pressure on the working surface on a par with mass production bolts. This shape yielded the prospect of securing moldability without changing the existing mass production process or materials. The change in bolt head shape also necessitated a change in the shape of the probe that faces it. With this measurement method, however, it is the propagation medium, not the probe, that serves as the surface coming in contact with the bolt. The propagation medium is formed from resin materials and is made

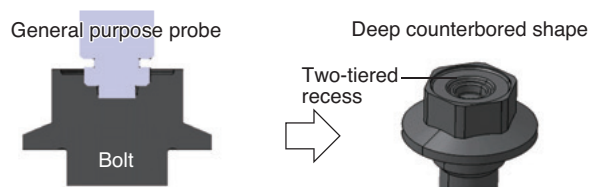


Fig. 14 Deep counterbored shape of bolt head

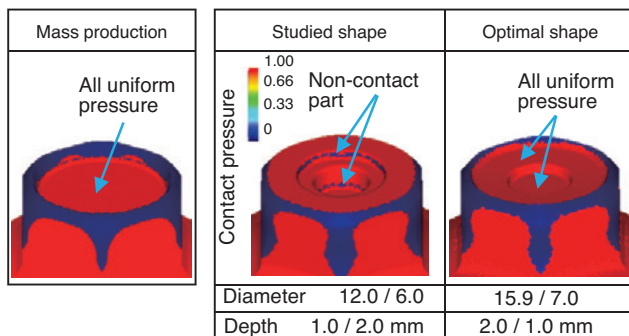


Fig. 15 Comparison of molding analysis

detachable so that it can change readily to conform to the bolt head shape.

4.4.2. Molding verification in the bolt mass production process

The mold was fabricated based on the molding analysis results and molding verification was carried out on the mass production line (using 1,000 samples). Figure 16 shows the tolerance process capabilities for the set dimensions. As this indicates, the recess diameter, gap depth, and parallelism between measurement surfaces that are important to ultrasonic wave axial force measurement exceed the general process capability index of 1.33 by a large amount⁽²⁰⁾, and moldability equal to the molding analysis was achieved.

The dimensional accuracy required for bolts in ultrasonic wave axial force measurement was secured by means of these results. It became possible to manufacture the bolts by the same molding process used for existing mass production molded bolts without having to add further processes.

4.4.3. Fatigue strength characteristics

The application of axial force to the bolt causes tension from the screw portion and repulsive force from the flange seating surface to intersect so that a concentration of stress occurs below the neck where the flange terminates. Figure 17 shows the sectional shape of the developed bolt. As this indicates, the developed bolt has a two-level recess shape in the bolt head, and the distance from the recess bottom to the bottom surface of the flange is short by comparison with the

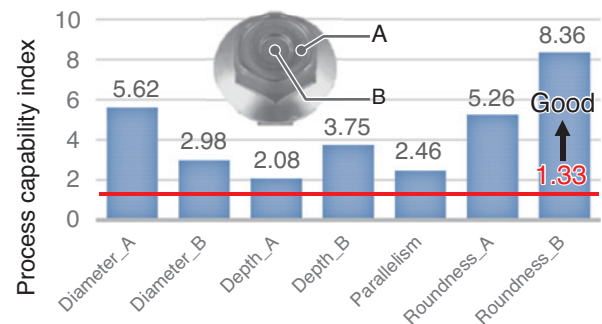


Fig. 16 Tolerance process capability index

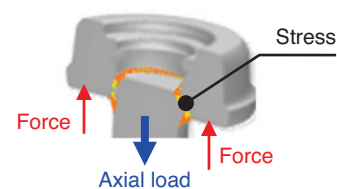


Fig. 17 Stress concentration by bolt fastening

ordinary bolt shape. This makes stress tend to concentrate. For this reason, it was necessary to help assure the fatigue strength in order to secure adequate performance against fracturing from long-term use.

Therefore the tensile fatigue test prescribed in JIS B 1081⁽²¹⁾ was carried out as comparative verification testing of the fatigue strength and fracture locations in the developed bolt and the mass production-based bolt. Figure 18 shows the results.

The test results show that under conditions of average stress at 70% of standard yield load (in the case of bolts, axial force)⁽²²⁾ at 0.2% yield strength, fatigue strength results equal to the mass production-based bolts were obtained. In addition, the fracture sites all occurred in the screw portion, and it was confirmed that adding the shaped recess to the bolt head did not have any influence on fatigue strength.

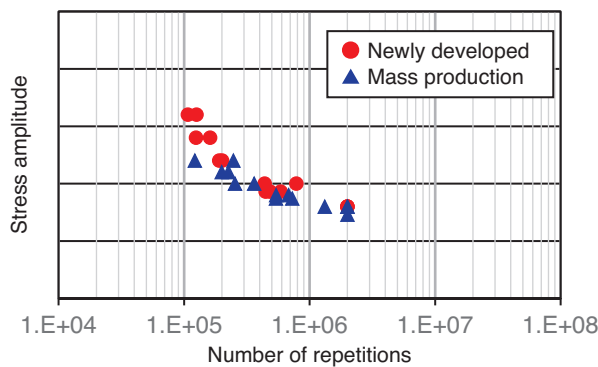


Fig. 18 Fatigue strength comparison test results

5. Fastening Verification Results

Verification was conducted to confirm the tightening accuracy of the real-time bolt axial force fastening system. For verification, six noise factors that are considered possible influences on ultrasonic wave axial force measurement were isolated and tests based on quality engineering methods⁽²³⁾ were carried out. As a result, sensitivity characteristics were obtained for the three factors of bolt effective diameter, grip length, and female screw length. Grip length is the length from the bolt neck under the flange part to the position where the female screw starts to engage. The female screw length is the actual length of the part where the female screw and male screw are engaged. These malfunction factors occur because of dimensional variations between individual products.

The M8 size bolt, which is used in mass production engines and has high accuracy requirements, was taken as the base for confirming tightening accuracy. Verification bolts were fabricated to reflect the upper, middle, and lower

limits in the drawing with respect to the three malfunction factors.

Verification bolts were used for confirmation and measurements were made five times ($n=5$) each for each factor alone and for their combinations. From the 1,000 measurement bolts manufactured in the mass production process, 30 bolts were added, making a total of 130 times ($n=130$) that tightening by axial force control was confirmed.

A tightening test jig with calibrated load cells built in, with the structure shown in Fig. 19, was used to carry out confirmation of the accuracy of ultrasonic wave axial force measurement. The test jig allowed movement and exchange of the female screw part, so the grip length and female screw length can be adjusted. The measurement accuracy was sought in this way from the difference between the load cell measurement value and the ultrasonic wave system measurement value.

The outcome was the favorable results obtained with a variation width of 0.96 kN ($\pm 3\sigma$) for the M8 bolt target tightening axial force value of 22.5 kN.

Figure 20 shows the fastening accuracy verification results for the real-time bolt axial force fastening system.

This is a variation of $\pm 2.1\%$ with respect to the axial force value taken as the target. Compared to the $\pm 30\%$ ⁽²⁾ when tightening with the torque method, this is a reduction to one-tenth or less.

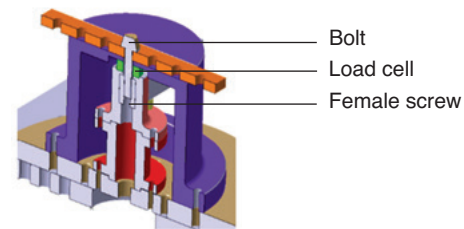


Fig. 19 Structure of test jig

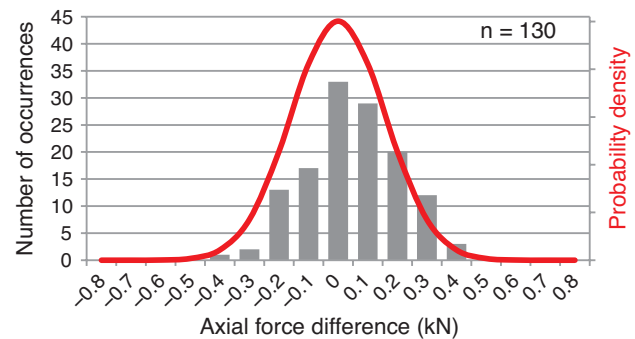


Fig. 20 Accuracy verification results for bolt axial force with this system

6. Conclusion

A real-time bolt axial force fastening system that is suited to axial force measurement under mass production assembly conditions was developed.

- (1) A two-gate measurement method with a gap opened in the bolt head was developed.
- (2) It became possible to obtain stable measurement results by means of two-gate tracking and a malfunction judging function.
- (3) The method was made adaptable to use in the mass production environment by developing a solid propagation medium using elastomer material in place of liquid together with a probe holding structure to deal with tilting of the measurement equipment.
- (4) Specification were created for bolts to use in measurement that can be produced without changing existing manufacturing methods, and increases in manufacturing costs were kept under control.
- (5) Axial force variations during fastening were successfully reduced to one-tenth or less by comparison with the torque method.

This technology addresses issues in the production processes for a wide range of industrial products and is thought to be a potentially important technology for increasing product strengths.

References

- (1) Teshima, Y., Gotoh, Y., Takahashi, N.: Non-destructive Slack Inspection Technique for High Tension Bolts using the Electromagnetic Phenomenon, *Journal of JSNDI*, Vol. 61, No. 5, p. 227-234, (2012) (in Japanese)
- (2) Ohashi, N., Hagiwara, M., Yoshimoto, I.: Characteristics of Bolted Joint in Plastic Region Tightening, *Journal of the Japan Society of Precision Engineering*, Vol. 51, No. 7, p. 1383-1389, (1985) (in Japanese)
- (3) JIS Z 2353: Method for measurement of ultrasonic velocity in solids, (2021)
- (4) <http://usmaj.o.oo7.jp/shindoshi.html>
- (5) Shigeno, N.: 3.5.2 Tanshokushi No Shurui To Yoto, Hihakai Kensa Gijutsu Shirizu Choonpa Tansho Shiken II, The Japanese Society for Non-Destructive Inspection, p. 36-37, (2000) (in Japanese)
- (6) Makino, T., Sakai, T., Toriyama, H.: Choonpa O Riyo Shita Boruto Jikuryoku Sokutei Sochi No Kaihatsu To Jitsuyoka, *Journal of the Japan Society of Precision Engineering*, Vol. 43, No. 2, p. 227, (1977) (in Japanese)
- (7) Ito, Y.: Method of Generating High-intensity Aerial Ultrasonic Waves and Its Applied Technologies, *IEICE Fundamentals Review*, Vol. 9, No. 3, p. 205-213, (2016) (in Japanese)
- (8) Hosaka, Y., Imano, K.: Strobe Photo-elastic Visualization of Ultrasound Propagation in the Residual Stress Field of the Solid, *Journal of the Society of Materials Engineering for Resources of Japan*, Vol. 27, No. 1/2, p. 20-24, (2016) (in Japanese)
- (9) JP, 2020-020749, A
- (10) JP, 2020-020763, A
- (11) JP, 2021-148629, A
- (12) JIS Z 2350: Method for measurement of performance characteristics of ultrasonic probes, (2002)
- (13) JIS K 6253-3: Rubber, vulcanized or thermoplastic -- Determination of hardness -- Part 3: Durometer method, (2012)
- (14) JP, 2020-019124, A
- (15) JP, 2021-196268, A
- (16) <https://www.nittokog.co.jp/fastenerscatalog/F-TOKUHIN-R.pdf>
- (17) Anan, G., Namimura, Y., Hasegawa, T., Oki, Y.: Development of Wire Rods with Improved Cold Headability, *R&D KOBE STEEL ENGINEERING REPORTS*, Vol. 48, No. 1, p. 39-42, (1998) (in Japanese)
- (18) JIS B 1051: Mechanical properties of fasteners made of carbon steel and alloy steel -- Bolts, screws and studs with specified property classes -- Coarse thread and fine pitch thread, (2014)
- (19) JP, 2020-020453, A
- (20) Nagata, Y., Munechika, M.: Dai 1 Sho, Kotei Noryokushisu No Teigi To Hyokakijun, Kotei Noryokushisu, Jissen Hoho To Sono Riron, Japanese Standards Association, p. 17-24, (2011) (in Japanese)
- (21) JIS B 1081: Threaded fasteners -- Axial load fatigue testing -- Test methods and evaluation of results, (1997)
- (22) Hagiwara, M.: Fatigue Fracture of a Bolt in Bolt/Nut Assembly, *Journal of the Japan Society for Precision Engineering*, Vol. 81, No. 7, p. 623-627, (2015)
- (23) Yano, K.: Fundamentals of Quality Engineering and Parameter Design, *Journal of the Japan Society for Precision Engineering*, Vol. 81, No. 11, p. 1008-1012, (2015)

■ Author ■



Kazuhiro TSUZAKI



Toshitsugu SAKAKIBARA



Yasushi HARA



Tsukasa ISHIDA