Contact Pressure Measurement by Means of Ultrasonic Waves*  
(On a Bolted Joint with a Solid-metal Flat Gasket)

By Yoshihisa MINAKUCHI**

A quantitative measurement of contact pressure by means of ultrasonic waves using a normal probe has been proposed to measure the contact pressure on a bolted joint with a solid-metal flat gasket. At first, in a proposed calibration method, the relation between mean contact pressure and sound pressure of reflected waves is obtained using the calibration blocks with various surface roughnesses and heights made of the same material as the bolted joint. Both sides of the laminated finite hollow cylinders are compressed under a locally uniform pressure, and the sound pressure of reflected waves is measured. From these relations, the contact pressure is obtained. The experimental results agree approximately with the theoretical ones. It is demonstrated that the gasket has an effect of preventing the leakage and the proposed ultrasonic method is practically useful.

Key Words: Experimental Stress Analysis, Contact Pressure, Ultrasonic Waves, Normal Probe, Quantitative Measurement, Bolted Joint, Solid-metal Flat Gasket, Seal Efficiency, Finite Hollow Cylinder

1. Introduction

It is important to have an exact information about the contact pressure distribution in the design of connected parts of machines and apparatus. In earlier works, stress analyses of a two body contact problem have been carried out in large numbers. Besides, there have been several studies on the measurement of contact pressure, for example, methods of photoelasticity [1], pressure-sensitive paper [2], pressure sensitive paper [3], changes of surface roughness [4] and ultrasonic waves [5-12]. However, a quantitative measurement of contact pressure in each measuring method seems to leave various problems to be solved. Particularly, the measuring method of contact pressure by means of ultrasonic waves has attracted attention as the only method capable of measuring the real contact pressure without changing characteristics on the contact surface. But few studies for a quantitative measurement of contact pressure seem to have been done yet [5-12], and the practical usefulness of this measuring method is not yet investigated sufficiently.

In this paper, applying the quantitatively measuring method of contact pressure proposed by a previous report [13], the contact pressure distribution on a bolted joint inserted with a solid-metal flat gasket is investigated, which is often used to improve the seal efficiency on the connected parts of machine structures. In this experiment, the bolted joint with the solid-metal flat gasket inserted be-

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the heights of calibration blocks \( h_1 = 30 \text{ mm} \), \( h_2 = 6 \text{ mm} \), \( h_3 = 68 \text{ mm} \) kept constant, the roughness at the contact surface of the calibration block (I) attached with a normal probe was changed by lapping or grinding (Nos.1 ~ 5 in Table 1). The latter influence was investigated by changing \( h_1 \) to 30, 45, 60 mm after the surface was lapped with \#1000 grain, because the surface of the calibration block (I) should be finished as even as possible (Nos.2, 6, 7 in Table 1). Besides, the calibration block (II) was made of a plate cut from alumin plate used as a solid-metal flat gasket without processing. The calibration block (III) was lapped taking care about the flatness accuracy, and the influence of sound pressure of reflected waves at the contact surfaces in the calibration blocks (I) and (II) was minimized. A compression test of the calibration blocks was done as shown in Fig.2 in which the contact pressure was uniform and the sound pressure of reflected waves was obtained stably. Here, the weight of normal probe (3N) was used so that the normal probe did not move and the contact pressure of it did not change under loading. The contact surfaces of calibration blocks were degreased with acetone to a state of no lubrication. The compressing method of calibration blocks was similar to the method in the previous report and the sound pressure of reflected waves at the contact surface of the calibration blocks (I) and (II) was read from the height of the first reflected echo by an ultrasonic device. A calibration curve between sound pressure of reflected waves and contact pressure was drawn.

The calibration test was done for the combination of No.2 in Table 1 using a normal probe A (frequency \( f = 10 \text{ MHz} \), diameter of transducer \( d = 0.5 \text{ mm} \)) and for every combinations in Table 1 using a normal probe B (\( f = 10 \text{ MHz}, d = 0.1 \text{ mm} \)). Here, the coupling medium was used a machine oil (\#120), and the longitudinal wave velocity in the calibration block (I) was 5,900 m/s.

3.2 Compression test of laminated finite hollow cylinders

Concerning a bolted joint with a solid-metal flat gasket inserted between two finite hollow cylinders, the influences of the plate thickness, Young's modulus and the load on the contact pressure were investigated using the experimental model as shown in Fig.3. Here, \( E_1, E_2, E_3 \) and \( \nu_1, \nu_2, \nu_3 \) are respectively Young's moduli and Poisson's ratios. The dimensions of finite hollow cylinders used in the experiment were \( 2a = 22 \text{ mm}, 2b = 160 \text{ mm} \), and the contact surfaces of the finite hollow cylinders (I) and (III) were lapped after grinding. These surfaces were finished so as to keep the same contact state as that of the calibration blocks composing of Nos.2,

<table>
<thead>
<tr>
<th>No.</th>
<th>Block</th>
<th>( h_1 )</th>
<th>( h_2 )</th>
<th>Condition of contact surfaces</th>
<th>Machining method</th>
<th>Material</th>
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Fig.1 Dimensions of calibration blocks

Table 1 Shapes and material properties of calibration blocks (I)~(III)

Fig.2 Compressive method of calibration blocks
6, 7 in Table 1. The finite hollow cylinder (II) was made of a plate cut from aluminum as a solid-metal flat gasket. Table 2 shows the combinations of their finite hollow cylinders.

Next, a compression of three laminated finite hollow cylinders was carried out with cylindrical blocks corresponding to the bearing surface of a bolt (material: S 45 C, inner diameter: 20 mm, outer diameter: 30 mm) placed on both sides of them. After a normal probe A or a normal probe B was set on the finite hollow cylinder (I) using a weight (2.25 N for probe A, 3.66 N for probe B) and guide plates, the load \( W \) was applied by means of fastening nuts using an experimetal apparatus as shown in Fig.4. The magnitude of the load was detected with a load cell. On the other hand, the sound pressure of reflected waves at the contact surface between finite hollow cylinders (I) and (II) was read from the height of the first reflected echo when the load was changed at the measuring position of each contact pressure. Moreover, the experiment was carried out using respectively the normal probe A at the position of \( r=21 \text{ mm} \) and the normal probe B at the other positions of \( r=25, 30, 35, \ldots \) 70 mm. The measured value of the longitudinal wave velocity in the finite hollow cylinder (I) was 5900 m/s.

4. Experimental Results and Considerations

4.1 Calibration curves

Figs. 5, 6 are the results of the calibration curves on the relations between mean contact pressure and characteristic of reflected waves at the contact surface of the calibration blocks (I) and (II). The mean contact pressure \( P_c \) is defined as the load divided the cross-sectional area \( (225 \times \text{mm}^2) \) of the calibration block assuming the contact pressure to be uniform. The characteristic of reflected waves \( E_i \) is given by

\[
E_i = 1 - \frac{h_s}{h_o}
\]

where \( h_o \) and \( h_s \) are the heights of the first reflected echo from the contact surface under no loading and under loading, respectively. \( PW \) shown in these figures is the pulse width.

Fig.5 shows the measured results on the changes in the characteristic of reflected waves against the changes in the surface roughness of the calibration block (I), the heights of which are \( h_s=30, 60, 68 \text{ mm} \). From the figure, it is found that the characteristic of reflected waves \( E_i \) becomes smaller and the change in the sound pressure of reflected waves decreases more as the surface becomes rougher. In this case, the change in new contact parts due to the ununiform surface roughness under increasing load and the damping of wave due to the scatter of through media have no influence on the sound pressure of reflected waves. The relation between contact pressure and sound pressure of reflected waves is almost linear. The results of No.2 in Fig.5 and Nos. 6, 7 in Fig.6 show the case where the height of the calibration block (I) \( h_s \) is 30, 45 and 60 mm. In these results,
the values of $p_w/E_1$ in the case of $h_1$ being 30, 45, 60 mm are scarcely different. Namely, if the thickness change of a measured object is in the range of 30~60 mm, the influence of the characteristic of reflected waves is little. Besides, the measured gain becomes as large as 19, 21, 23.5 dB when $h_1$ becomes as large as 30, 45, 60 mm. As shown in the previous report\(^\text{[10]}\), it is likely that the damping of ultrasonic waves becomes larger on account of the scatter at grain boundary and the internal friction when the distance through media becomes larger.

Fig.7 shows that the changes in the surface roughness of the calibration block (I) have influences on the value of $p_w/E_1$. The increment of the value of $p_w/E_1$ is more remarkable as the surface becomes rougher.

![Fig.5](image1.png)  
**Fig.5** Relations between mean contact pressure $p_w$ and characteristic value of reflected waves $E_1$

![Fig.6](image2.png)  
**Fig.6** Relations between mean contact pressure $p_w$ and characteristic value of reflected waves $E_1$

![Fig.7](image3.png)  
**Fig.7** Effect of the surface roughness of calibration block (I) on the $p_w/E_1$ value ($h_1=30$ mm, $h_2=6$ mm, $h_3=68$ mm)

![Fig.8](image4.png)  
**Fig.8** Characteristics of reflected waves when the load was applied to laminated finite hollow cylinders (No.4 in Table 2)
4.2 Characteristics of reflected waves on laminated finite hollow cylinders

Fig.8 shows the characteristics at the contact surface between finite hollow cylinders (I) and (II) when the load W was applied to laminated hollow cylinders under the combination of No.4 in Table 2. The pressure p is defined as the load divided by the cross-sectional area (125mm²) of hollow blocks. The measured result at each contact pressure changes almost linearly, and the slope becomes gentle as the measuring position moves away from the load position and the slope is horizontal at r=60 mm. Namely, the sound pressure of reflected waves at r=60 mm is equal to that under no loading, and its position is found to be the separation point on the contact surface.

4.3 Calculations of contact pressure distributions

The contact pressure distribution of laminated finite hollow cylinders as shown in Fig.8 is calculated using the calibration curve of No.6 in Fig.6 in which the plate thickness is 45mm. When the thicknesses of the finite hollow cylinder (I) attached with a normal probe are 30mm and 60mm, the calibration curves of No.2 in Fig.5 and No.7 in Fig.6 are used. Besides, the measured gains in the curves of Fig.8 and the calibration curves are considerably different from each other. The effect of noise with a increasing gain seems to be the cause of the measured error. But in this experiment, the contact pressure is calculated neglecting this effect.

4.4 Pressure distributions on the contact surface

Fig.9 indicates the experimental results of the pressure distribution on the contact surface (z=h/2) with the marks O, △ and □. The solid lines indicate

(a) Effect of plate thicknesses ratio

(b) Effect of Young's moduli ratio

(c) Effect of the ratio of plate thicknesses and load width

Fig.9 Pressure distributions on the contact surface
the results calculated with the Bessel series cut off at 50 terms by the reference (13) for the analytical model of Fig.3. Figs.9(a)−(c) show that the plate thicknesses ratio, Young's moduli ratio and the ratio of plate thicknesses and load width have effects on the contact pressure distribution. Fig.9(a) shows the result when Young's moduli ratio $E_1/E_0 = 1$. $h_1/h_0 = 0.5$ are constant and the plate thicknesses ratio $h_1/h_0$ changes. It is seen that the maximum contact pressure becomes larger and the separation point on the contact surfaces comes closer to the loading position as $h_1/h_0$ becomes smaller. Fig.9(b) shows the result when the plate thicknesses ratios $h_1/h_0 = 0.5$, $h_1/h_0 = 1$ are constant and Young's moduli ratio $E_1/E_0$ changes. It is found that the maximum contact pressure becomes smaller and the pressure distribution is gentle and the estimated separation point on the contact surfaces, where the sign of $(a_{n+1}-a_n)/D$ changes from positive to negative, tends to deviate from the loading point as $E_1/E_0$ becomes smaller. Namely, if Young's modulus $E_1$ of the solid-metal flat gasket is smaller than $E_0$ or $E_0$, the region of the contact pressure expands and the seal efficiency of the gasket is better. Fig.9(c) shows the case where the plate thicknesses ratio, Young's moduli ratio and the size of the load are constant and only the plate thickness changes. It is shown that the maximum contact pressure becomes larger and the estimated separation point on the contact surfaces comes closer to the loading position as the plate becomes thinner. Moreover, the broken lines in the figure represent the calculated results except the solid-metal flat gasket. Unlike the case where the solid-metal flat gasket is used, the maximum contact pressure is large and the estimated separation point on the contact surfaces is located near the loading position.

The experimental results as shown in Fig.9 agree fairly well with the calculated ones except in the region of small contact pressure. The separation point on the contact surfaces obtained by the experiment is found to be located near the loading position. The cause of this measuring error is considered that the contact surfaces of the finite hollow cylinders (I) and (III) were convex and the effect of their flatnesses on the contact pressure appeared.

From the results described above, if the experiment is carried out taking care of the surface roughnesses and the flatnesses on both the calibration block and the measured object, a quantitative measurement of contact pressure is found to be fairly practical for use on this problem.

5. Conclusions

In this paper, a contact pressure on a bolted joint with a solid-metal flat gasket inserted between two finite hollow cylinders was measured quantitatively by means of ultrasonic waves using a normal probe. Therefore, the surface roughnesses and the heights of calibration blocks adopted for measuring the contact pressure quantitatively were investigated for the effect of the measured results. The experimental results were compared with the analytical ones, and the following conclusions were obtained.

(1) The experimental results obtained by this method agree fairly well with the analytical ones except in the region of small contact pressure. From these results, it is seen that this method is fairly practical for use.

(2) The plate thicknesses ratio, Young's moduli ratio and the load are made clear about the effect of the contact pressure, and the seal efficiency of solid-metal flat gasket is pointed out.

(3) The change in the sound pressure of reflected waves becomes smaller as the contact surface of measured object becomes rougher.

(4) If the thickness change of the measured object is within 30−60 mm, the characteristic of reflected waves has no influence on this thickness.

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