Contact Pressure Measurement by Means of Ultrasonic Waves*

(On a Method of Quantitative Measurement)

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A quantitative measurement of contact pressure by means of ultrasonic waves has been proposed to measure the contact pressure distribution between two elastic beams. At first, in a new proposed calibration method, the relation between mean contact pressure and sound pressure of reflected waves is obtained by using calibration blocks made of the same material and height as the beams. After such preparation, both sides of the laminated beams are compressed under locally uniform pressure, and the sound pressure of reflected waves is measured. From these relations, the contact pressure in beams is directly obtained. It is clarified that the experimental results agree approximately with the theoretical ones and the proposed ultrasonic method is practically useful.

Key Words : Experimental Stress Analysis, Contact Pressure, Ultrasonic Waves, Quantitative Measurement, Probe

1. Introduction

It is important to have exact information about the contact pressure distribution in the design of connected parts of machine structures. In earlier works, stress analyses on a two body contact problem have been carried out in large numbers. Besides, the measurement of contact stress is important to confirm the adequateness of the theoretical analysis and to know the practical pressure distribution, but an excellent measuring method can't be found at present. There have been several studies on the measurement of contact pressure between two elastic bodies, for example, methods of photoelasticity⁽¹⁾, pressure-sensitive pins⁽²⁾⁻⁽⁵⁾, pressure sensitive papers⁽⁶⁾, changes of surface roughness⁽⁷⁾⁽⁸⁾ and ultrasonic waves⁽⁹⁾⁻⁽¹⁴⁾. However, the accuracy in each measuring method would seem to be not still satisfactory. Particularly, the method by means of ultrasonic waves has been studied considerably by Ito et al.⁽¹¹⁾⁻⁽¹⁴⁾ as the only method capable of measuring the real contact pressure without changing characteristic on the contact surface. This method is applicable for a qualitative measurement of contact pressure at present, but studies of quantitative measurement would seem to have not been done yet.

In this paper, in order to expand the

applicable range of the contact pressure measurement by means of ultrasonic waves, the relation between sound pressure of reflected waves and contact pressure is obtained beforehand by compressing calibration blocks made of the same material and height as measuring objects. Using this result, we tried to measure the contact pressure quantitatively. In an experiment, the pressure distribution on the contact surface in which both sides of two laminated beams are compressed is measured. The experimental results are compared with the analytical ones and the experimental results of pressure-sensitive pin method⁽⁴⁾, the measured accuracy and the practical usefulness of this measuring method are investigated.

2. Principles of Contact Pressure Measurement and Proposals of Quantitative Measuring Method

2.1 Principles of measurement

The reflection and the transmission of waves occur as shown in Fig.1 when a perpendicularly incident wave reaches a boundary plane where the sound characteris-

Fig.1 Reflection of plane wave at boundary plane

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tics on both media differ from each other. At the boundary plane, part of the plane wave is reflected and transmitted. In this case, the relation between sound pressure of reflected waves P_r and incident waves P_i is given by

$$P_r = R_p P_i \dots\dots\dots (1)$$

where R_p is the rate of the reflection of the sound pressure. When the sound characteristics on both media are equal, the real contact part is $R_p=0$ and the other part is $R_p=1.0$ at the contact surface in solid contact states.

Now, it is already clear that the relation between normal load acting on the contact surface and area of the real contact part is almost proportional⁽¹⁵⁾ or proportional⁽¹¹⁾ when the deformation in contact points is perfectly plastic or elastic. Since the practical contact surface can be considered as an elastic-plastic deformation, the area of the real contact part increases proportionally with an increment of the normal load acting on the contact surface. Namely, the contact pressure measurement by means of ultrasonic waves is a method in which the change of the real contact area is detected as the sound pressure of reflected waves by using the ultrasonic device. If new contacts do not appear when the load increases and the damping of waves due to a scatter of waves is not taken into account, the relation between sound pressure of reflected waves and contact pressure in these ideal cases gives straight lines. But the actual relation seems to be not always linear⁽¹¹⁾.

2.2 Proposals of quantitative measuring method

For the reason stated in Section 2.1, the measurement of contact pressure by means of ultrasonic waves has been utilized as a qualitative measurement until now. However, a quantitative measurement is expected to expand the applicable range of this measuring method.

In this study, the quantitative measuring method of contact pressure is proposed by using standard calibration blocks. Namely, the relation between sound pressure of reflected waves and contact pressure is obtained by compressing the calibration blocks made of the same material and height as measuring objects. Next, we measure the sound pressure of reflected waves at the contact surface when the measuring objects are compressed at the measuring position of each contact pressure. Finally, the contact pressure is measured quantitatively by using the calibration curve for the measured results. According to this method, the contact pressure can be measured on condition that the actual measurement is considerably close to the calibration curve. Moreover, since the difference of contact surface states on calibration blocks and measuring objects has a large influence on the measured accuracy, respective surfaces should be finished as uniform as possible and have identical contact states.

3. Experimental Method

In order to investigate a quantitative measuring method of contact pressure by means of ultrasonic waves, let's consider an experimental model as shown in Fig.2 in the case where both sides of two laminated beams with different thicknesses are subjected to a uniformly distributed pressure p over width $2a$ with total load W . E_1, E_2 and ν_1, ν_2 indicated in the figure are Young's moduli and Poisson's ratios, where suffixes 1 and 2 designate the beams (I) and (II).

Fig.3 shows the dimensions of beams (I) and (II) used in the experiment. Table 1 shows the details of their combinations. Besides, both sides of the beams were ground and their contact surfaces were lapped with #1000 grain so as to keep surfaces as uniform as possible. The surface roughness and the flatness in Table 1 show the values of the lapped surfaces.

At first, in order to clarify the relation between sound pressure of reflected

Fig.2 Experimental model

Fig.3 Dimensions of beams (I) and (II)

Table 1 Shapes and material properties of beams (I) and (II)

No.	Beam	h ₁ h ₂ mm	Material	E ₁ E ₂ Gpa	ν ₁ ν ₂	Condition of contact surfaces		
						Roughness μm R _{max}	Flatness μm	Machinin method
1	I	30	S45C	206	0.3	0.9	2.0	Lapping
	II	30				0.7		
2	I	30				0.9		
	II	45				0.8		
3	I	30				0.9		
	II	60				0.7		

waves and contact pressure, we produced a cylindrical calibration block (I) (called calibration block) made of the same material (S45C) and height (30 mm) as the beam (I) for attaching a probe and a calibration block (II) (material: S45C) for supporting it. Fig.4 shows the dimensions of the calibration blocks (I) and (II). Both sides of them were ground and their contact surfaces were lapped with #1000 grain so as to keep the same contact states as the contact surface of beams. The flatness of them is $0.9\mu\text{m}$ and the surface roughness is shown in Fig.5. Fig.6 shows a compressive method in which the contact pressure of calibration blocks is uniform and the sound pressure of reflected waves is obtained stably. In this method using a weight (3.03 N), a probe does not move and then the contact pressure of it does not change under loading. Fig.7 shows a compressive apparatus for calibration curve. The load is applied by fastening nuts and the magnitude of it is detected with a load cell. On the other hand, the sound pressure of reflected waves at the contact

Fig.4 Dimensions of calibration blocks (I) and (II)

Fig.5 Surface roughnesses of calibration blocks (I) and (II) (R)

surface of calibration blocks is read from the height of the first reflected echo by an ultrasonic device and a calibration curve between sound pressure of reflected

Fig.6 Rough sketch of compressive method

Fig.7 Compressive apparatus for calibration curve

Fig.8 A weight and guide plates for probe

waves and contact pressure is drawn.

Next, after attaching steel blocks (material: S45C, width: $2a=20$ mm, depth: 45 mm) on both sides of the two laminated beams, a weight and guide plates for probe are set on the beam (I) as shown in Fig.8. In this case, the probe does not move and the contact pressure does not change under loading. Fig.9 shows an experimental apparatus. In order to measure exactly the sound pressure of reflected waves at the contact surface, the height of the first reflected echo when the load was applied at the measuring position of each contact pressure is measured.

Moreover, the experiment is done after the load was applied beforehand several times in order to stabilize the surface state. The surfaces of beams and calibration blocks were well degreased with acetone to a state of no lubrication. The probe whose oscillating frequency was 10 MHz and whose diameter was 5 mm and whose coupling medium was used machine oil #120. The longitudinal wave velocity in the calibration block (I) and the beam (I) was 5900 m/s.

4. Comparison of the Experimental Results with Calculated Ones and Considerations

Fig.10 shows the calibration curve on the relation between mean contact pressure and characteristic of reflected waves. The mean contact pressure p_m is defined as the load divided by the cross-sectional area ($225\pi \text{ mm}^2$) of the calibration block. The characteristic of reflected waves E_R^* is given by

$$E_R^* = 1 - \frac{h_e}{h_{e0}} \quad (2)$$

where h_{e0} and h_e are the height of the first reflected echoes at the contact surface under no loading and under loading, respectively. From the figure, the calibration curve is seen not to be influenced very much by the increment of new contact parts due to the roughness and winding of the contact surface and the damping of

Fig.9 Experimental apparatus

ultrasonic waves stated in Section 2.1. Approximately straight lines are given under loading up to 15.7 kN. The difference in the value of E_R^* with an increase and with a decrease of the load is little.

Fig.11 shows the measured results of the characteristic E_R^* when the load was applied to the laminated beams under the combination of No.3 in Table 1. The pressure p is defined as the load divided by the cross-sectional area ($20 \times 45 \text{ mm}^2$) of compressive steel blocks. The relation between load and characteristic of reflected waves E_R^* changes almost linearly. The slope of the curves becomes smaller as the measuring position of contact pressure moves away from the loading position and the curves are horizontal at $r \geq 40$ mm.

Fig.10 Relation between mean contact pressure p_m and characteristic value of reflected waves E_R^* (gain: 31dB, pulse width: 0.508 μ s)

Fig.11 Measured results of characteristic of reflected waves under loading (gain: 31.5dB, pulse width: 0.508 μ s)

Namely, each sound pressure of reflected waves at $x \geq 40$ mm is equal to that under no loading. It is found that the contact surface separates beyond $x=40$ mm. The pressure distribution on the contact surface is obtained from the relation between the measured curves in Fig.11 and the calibration curve in Fig.10.

Fig.12 indicates the experimental results of the pressure distribution with the marks $\circ$, Δ and $\square$. Besides, the solid lines indicate the results calculated with the Fourier series cut off at 40 terms by reference (16) for the analytical model of Fig.2. Though it is not likely that the practical load distribution agrees with that of the analytical model, the effect of the difference of both load distributions on the contact pressure is little because the contact surface is enough away from the load part. Therefore, it seems that the accuracy of the experimental results can be estimated from the calculated results. Comparing the experimental results with the calculated ones, the experimental result in the case of the heights ratio of beams being $h_2/h_1=60/30$ agrees fairly well with the calculated one except the region of small contact pressure. Besides, it is seen that the separation point on the contact surface obtained by the experimental results comes closer to the loading position than the estimated separation point on the contact surface, where the sign $(\sigma_y)_{y=0}/p$ changes from positive to negative. The results of $h_2/h_1=45/30, 30/30$ show a similar tendency to the result of $h_2/h_1=60/30$. But in the combinations that the height of beam h_2 is small, the difference between the experimental and calculated results tends to become larger as the contact pressure $(\sigma_y)_{y=0}/p$ becomes smaller. The measured results of ultrasonic waves are smaller than these of pressure-sensitive

pin⁽⁴⁾ with the marks $\bullet$, $\blacktriangle$ as the contact pressure becomes smaller.

The factors affecting the above-mentioned difference are as follows:

- (1) The range in which ultrasonic waves act on the measuring surface is wide.
- (2) The roughnesses of the contact surfaces on the calibration blocks and the beams are not equal.
- (3) The roughness of the contact surface on the beams is not uniform and windings occur.

First of all, on the subject of (1), the range in which ultrasonic waves act on the measuring surface will be calculated. The divergence angle of the probe at far field is approximately given by

$$\theta_0 \approx 1.22(\lambda/2R)$$

where θ_0 (rad) is the divergence angle, λ is the wavelength of ultrasonic waves and R is the radius of crystal. In the case where the oscillating frequency is 10 MHz, $R=2.5$ mm and the longitudinal wave velocity is 5900 m/s, θ_0 is 0.14 rad. Accordingly, the range in which ultrasonic waves act on the measuring surface is $\phi 8.5$ mm when the height of beam is 30 mm. It seems that the mean contact pressure within the range of diameter (5 mm) of crystal can be measured. The range in which ultrasonic waves act on the measuring surface is wide. Therefore, the contact pressure at the measuring point can't be measured exactly and the measured error becomes larger in the case where the contact pressure distribution does not become gentle. In order to measure exactly the contact pressure by using the ultrasonic waves, a probe with a small divergence angle should be used. On the subject of (2), the experimental result on the combination of $h_2/h_1=60/30$ agrees fairly well with the calculated one. If the surfaces of the calibration block and the beam are finished to the degree of this experiment, both results must be almost identical. On the subject of (3), the effect of the measured accuracy must be little because the surface states of both beams are approximately identical.

5. Conclusions

A method using calibration blocks has been proposed to measure quantitatively the contact pressure by means of ultrasonic waves. In order to investigate the practical usefulness of it, the contact pressure distribution in the case of compressing two laminated beams was measured. The experimental results were compared with the analytical ones and the results by means of the pressure-sensitive method, and the following conclusions are obtained.

(1) The relation between contact pressure and sound pressure of reflected waves is clarified by using calibration blocks made of the same material and height as measuring objects. Therefore, it is shown that the contact pressure can be measured quantitatively.

(2) If the surfaces of the calibration block and the measuring object are well lapped within the range of $0.7 \sim 0.9 \mu\text{m } R_{\text{max}}$, the measured results of contact pressure

Fig.12 Pressure distributions on the contact surface ($E_2/E_1=1$)

will be accurate enough for practical use.

(3) Since the change of sound pressure of reflected waves under loading is small, it is necessary to measure exactly the sound pressure of reflected waves by using a weight for the probe so that the contact pressure of probe can be kept constant.

(4) In order to measure exactly the contact pressure at the measuring point, a probe with a small divergence angle should be used.

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