AN ATTEMPT OF ESTIMATION OF SOLID CONTACT AREA RATIO USING LONGITUDINAL ULTRASONIC WAVE PULSES

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Abstract: Basic experiment for estimating a solid contact area ratio of dried interface by longitudinal ultrasonic wave pulses is attempted. The area ratio is estimated by echo height ratio H defined by sound pressure which depends on central frequency in one cycle of received waves. H is different by distance and topography of the solid contact part and wavelength, even if the solid contact area ratio is same. However, one law is clarified by arranging this relation with dimensionless distance $\Lambda(=\iota/\lambda)$ which depends on the distance ι of the solid contact point and the wavelength λ.

H is shown by a curve which depends only on the solid contact area ratio, and then, it for any area ratio monotonously approaches the non-contacting area ratio with increasing Λ. This tendency shows that the solid contact area ratio can be directly estimated from the echo height ratio measured by using the high frequency probe. Since the attenuation of the high frequency wave is remarkable, however, there is a limit of the measurement thickness. Therefore, the measurement by the low frequency probe is required. H in this region is not decided only by the non-contacting area and rapidly approaches to zero with decreasing Λ.

The behaviour of this H is governed with the stiffness of contacting two surfaces. Then, the equation for the estimation of the contact area ratio considering the effect of this stiffness is proposed. The solid contact area ratio estimated from H observed in the contact of two-dimensional regular rough surface with constant distance ι and smooth surface is almost agreed with the theoretical result.

Introduction: The friction and wear between two surfaces in contact, such as sliding contact under dry conditions, is determined in a complicated fashion by the modes of adhesion and growth of wear particles and the conditions between the two surfaces. A dependable method for measuring the contact conditions at both surfaces during actual contact is necessary in order to obtain some of the clues to solving these problems. The current well-known methods for measuring contact conditions are electrical resistance[1)], thermal resistance[2)], dye injection to the contact region[3)], and contact microscop[4)].

The contact electrical resistance method is often used in tests of conductive materials. It has been reported that the area of the solid contact region estimated using this method, by the change in electrical resistance due to contractive flow of the solid contact parts, agrees well with the theoretically predicted area[1)]. Oxidation on the surfaces severely disrupts the accuracy of this measurement, however, and it is impossible to carry out area measurements on moving surfaces, which are subject to constant formation and separation of oxidized layers. Furthermore, even stationary measurements are limited to certain materials. Contact microscopy allows precise measurements of the contact region area, including the essential parameter of contact distribution via a transparent material for one of the contacting samples used in the experiment. This type of microscopy exploits complete internal reflection to allow many useful observations, such as time-dependent or load-dependent histories of the contact region under stationary conditions and the dependence on speed or other parameters under rolling contact conditions. This method has provided a number of interesting discoveries revealing fundamental characteristics of friction, such as the increase in solid contact area with the passage of time and the decrease in solid contact area with rolling speed[4)].

It has been anticipated that an ultrasonic method, as employed in this study, will allow immediate measurement of the solid contact area from the C scope image of a stationary sample using an ultrasonic imager. A point-focus transducer for measuring water depth with a nominal center frequency of 25 MHz and −6 dB focus diameter of about 0.2 mm was attached as shown in Fig. 1. The focus was set to the area of contact between the acrylic sample and the supporting jig, and the area was scanned in the X and Y directions. Figure 2 shows an example of the resulting image. The bright parts of the image show where the sound waves easily penetrated the surface, indicating the locations of solid contact. The fraction α of the actual solid contact area A divided by the apparent solid contact area A_0, $\alpha = A/A_0$, is 0.37, and the aspect ratio of the bright portion of two-dimensional roughness (b) is about the same magnitude as the solid contact area ratio α. Thus, the estimated accuracy of the contact region area is higher under conditions in which α is large, but when the surfaces have high initial roughness, causing low α (a), the aspect ratio of the bright portions differed considerably from the observed $\alpha \cong 0.02$. In addition, when the roughness pitch ι, the major dimension of roughness in the solid contact region as a fraction of the diameter of the beam focus, is low, it is difficult to identify even the location of the contact region in the image. This is because the strength of the reflected echo under these conditions is determined by the mean reflected sound pressure from multiple contact regions and non-contact regions in the focus.

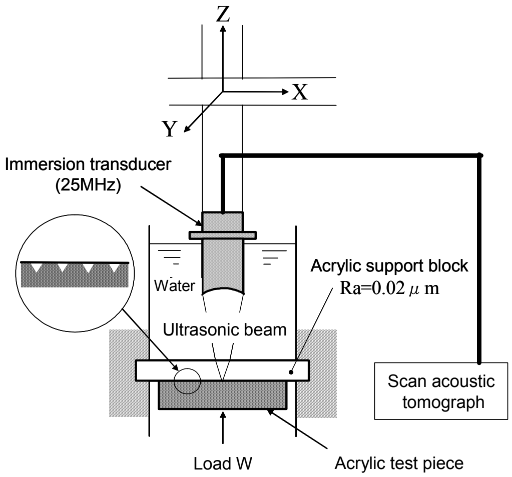


Fig.1 Test equipment

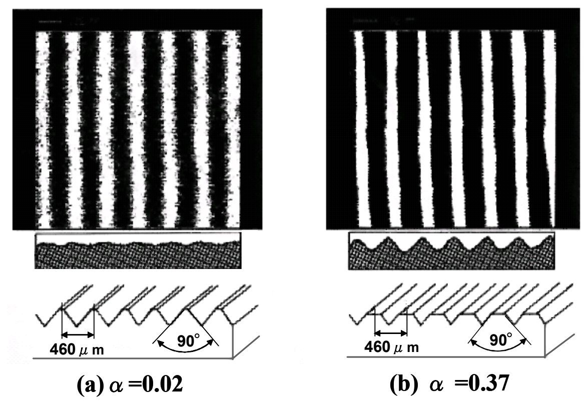
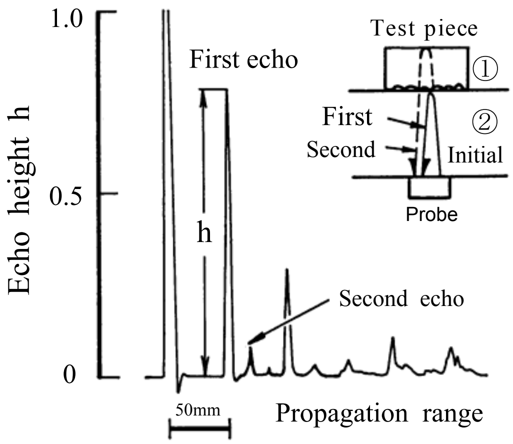


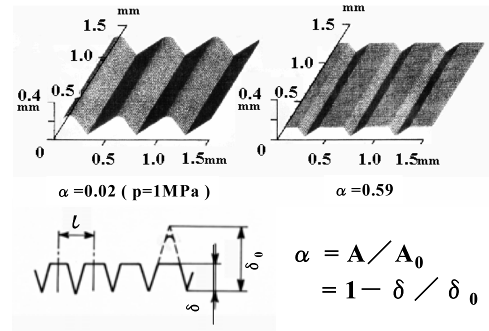
Fig.2 Image view of contact surface

Thus, it is difficult to obtain more detailed information by sonography than that provided by the contact microscope. This technique is mainly used to obtain mean area values, as described above. Nevertheless, the technique remains attractive because it is applicable for a wide variety of materials under both stationary and dynamic conditions, and is also simple and non-destructive. When multiple solid contact regions exist in the ultrasound focus, the strength of the acoustic signal returning from the contact interface (echo height) is thought to be proportional to the area of the solid contact region[5)]. However, the actual echo height depends not only on the contact region area, but also on the surface roughness and distortion at the contact region, its orientation, and the characteristics of the thickness transducer (for example, frequency-dependent characteristics)[6)]. As it remains unclear how much influence these factors have, quantitative solid contact region area measurements by this technique have been quite difficult.

In this study, some acrylic specimens with two-dimensional regular roughness and ultrasonic probes of differing frequency were used. The influence of the pitch of the solid contact region and of the acoustic wavelength was investigated under the dry condition, and the basic relationship between the echo height and the contact area was derived. These results will be used as the basis for proposing a convenient method considering the stiffness for estimation the solid contact area when it is not possible to identify the pitch or topography of the contact region. Then, the potential for the measurement of the solid contact area was examined.

Fundamental Relationship between Solid Contact Area Fraction and Echo Height Ratio: As shown in Fig.3, solid samples 1 and 2, made of the same material, were placed in contact and a transverse ultrasonic pulse was emitted by the transducer so as to exit from the lower face of sample 2. Part of the pulse passed through the contact region, and part was reflected there, constituting an echo[6)]. The echo height h diminishes with increasing solid contact area A within the area irradiated with the ultrasonic waves (area A_0). Thus, measuring the echo height allows estimation of the fraction α ($= A/A_0$) of the actual solid contact area[5)]. In order to eliminate the influences of acoustic pulse width, transmitted energy, contact medium, transducer attachment, and diffusion and scatter in the propagation path, the solid contact area is estimated using the echo height ratio $H = h/h_0$, where h is the primary echo height h under load and h_0 is the echo height in an isolated (no contact) specimen[8)]. The distance from the transducer to the supporting jig surface was set at 50 mm, far enough that the contact region was exposed to a nearly planar wavefront.





Test piece	ι, μm	δ_0, μm	Contact area ratio α =A/A_0			
I	130	52	0.02*	0.29	0.56	0.85
II	210	110	0.02*	0.22	0.47	0.69
III	460	220	0.02*	0.37	0.59	0.78

Fig.3 Measurement principle **Fig.4 2=dimensional regular rough surface**

Both the sample and the mirror jig were made of acrylic (PMMA). As shown in Fig.4, the sample surface contained regularly occurring ridge-shaped asperities (ridges) of even height. The ridges were parallel in a uniform direction, such that the roughness was two-dimensional. The specimen was made from 25 mm-diameter rod stock. The stock surface was used as-is in the first series of measurements, and then polished with #1500 emery cloth for the subsequent series of measurements. The table in Fig.4 shows the values of roughness pitch ι, maximum roughness, and the value of area ratio α indicated by a three-dimensional surface roughness meter. The truncated surface roughness in the ridgeline direction was Ra ≅ 0.08 μm (Ry ≅ 0.06 μm). The maximum waviness was about 0.3 μm/3 mm, and the radius of the asperities in the original sample surface was 20 μm in Sample I, 30 μm in Sample II, and 60 μm in Sample III. A very thin layer of lubricant just sufficient to cover just the roughness of the sample was applied to the jig surface and a load W was then applied to the sample to impart a mean pressure p (= W/A_0) of greater than 0.4 MPa. The echo height ratio H showed a constant value corresponding to α under these conditions. The value of H at a mean pressure of 1 MPa was used for area measurements, as this was judged from sonographic observations to force firm adhesion between the surfaces of the truncated surface and the jig.

Three transducers were used for the measurements. The central frequencies of the reflected waves were 1.64, 3.80 and 6.15 MHz. Figure 5 shows the relationship between echo height ratio H (= h/h_0) and area ratio α for Sample I (ι = 0.13 mm). The value of α for the sample with original roughness was found by assuming Hertzian contact and that all ridge peak radii on the cylinder were the same as the previously observed mean value. Even when α was the same, H takes different values at different ultrasound wavelengths λ, determined by the center frequency f of the reflected wave. The greater the frequency (the lower the wavelength), the greater the value of H. The dashed line in the chart refers to the straight line for H = (1 – α). The dashed line for H at λ = 0.72 mm (3.8 MHz) nearly matches this line. The regular relationship described above between λ and H broke down for Sample III, however. Here, the roughness pitch ι was 0.46 mm, about the same as the acoustic wavelength, as shown in Fig.6, and H was high at low frequencies. At λ = 0.72 mm, H showed a considerably higher value than that of the dashed line.

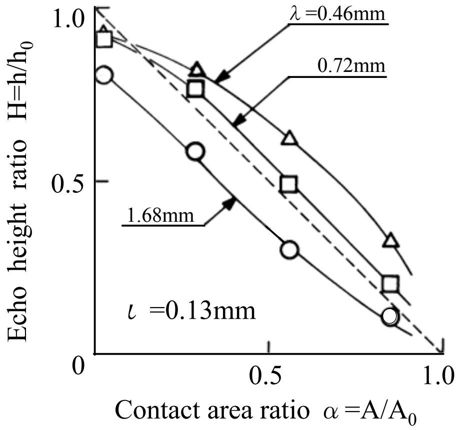


Fig. 5 Influence of wavelength (ι=0.13mm)

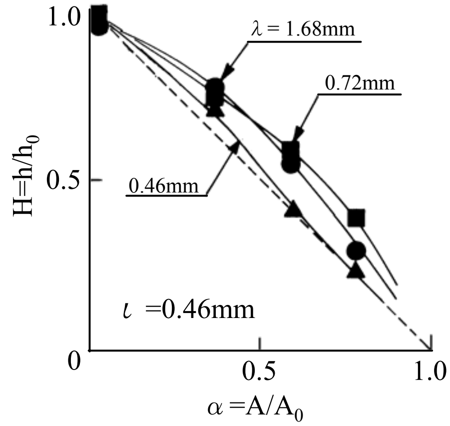


Fig. 6 Influence of wavelength (ι=0.46mm)

It is known that the reflectivity of acoustic waves from evenly spaced parallel surfaces, such as the long, narrow, evenly spaced defects in the samples in this experiment, is a function of the ratio between the pitch of the defects and the wavelength[7)]. Therefore, the results shown in Figs. 5 and 6 and those for Sample II are presented in Fig.7 with dimensionless pitch $\Lambda = \iota/\lambda$ on the horizontal axis, where ι and λ were defined as described above. The echo height ratio H is plotted for solid contact area ratios of 0.2, 0.4, 0.6, and 0.8. The fine line shows the results of Eq. (5), which takes the stiffnesses of the materials in the two faces into account. At first glance, the relationships in Figs. 5 and 6 appear to be irregular, but when reconsidered using the dimensionless pitch Λ, a clear relationship is revealed. The value of H with respect to constant α shows a gentle peak at around $\Lambda = 0.3$, and the curve can be broadly divided into 3 regions: H increases with Λ for $\Lambda < 0.3$–0.5, H is uniquely defined by α without influence of Λ at $\Lambda > 1.5$, and a transition in the behavior of H at Λ between these ranges.

The influence of ι disappears at high Λ. When Λ is greater than about 1.5, the following relationship is observed.

$$H=1-\alpha \tag{1}$$

Accordingly, if a high-frequency, short-wavelength transducer is used, it is immediately possible to infer the solid contact area ratio from the echo height ratio. However, it is not possible simply to select as high a frequency as possible in an actual instrument, since data are also subject to disruption by the diffusion and attenuation of the ultrasonic waves in the propagation path. Consequently, it is desirable to use a transducer with as low a value of Λ as possible, i.e., low frequency. This corresponds to the $\Lambda < 0.3$–0.5 region. Here, with the reduction in Λ, there is an abrupt increase in the transmissivity of the ultrasonic waves injected into the interface region. Even given the same solid contact area ratio, the echo height ratio tends to converge abruptly toward H=0.

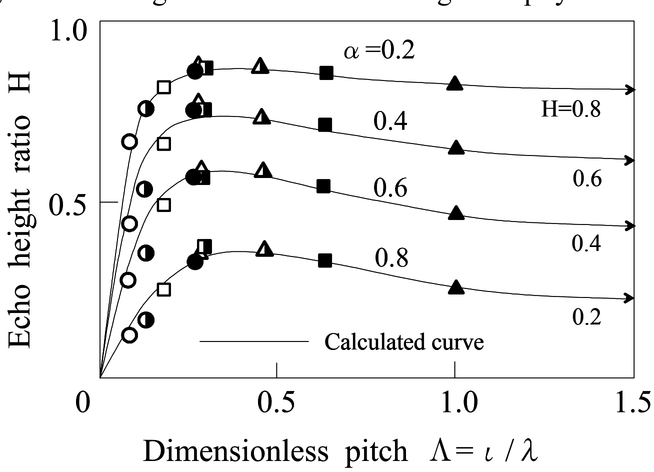


Fig.7 Relationship between Λ and H

Stiffness between Surfaces and Echo Height Ratio: Among many others, Kendall and Tabor et al. have examined reflection from and transmission through groups of regularly spaced, coplanar defects that are small with respect to the wavelength. Some of the results were summarized by Baik and Tompson et al[8]. Assuming conditions of quasi-static stress and identical materials of the two surfaces, as in the present study, the reflectivity R of acoustic waves from a contact region in incomplete contact is known to be given by

$$R = (\pi f Z / k) / \{ 1+(\pi f Z / k)^2 \}^{0.5} \quad (2)$$

Here, f is the wave frequency, Z is the acoustic impedance, and k is the spring constant of the material per unit area. For the present example of a surface with two-dimensional, regular roughness, this stiffness can be approximated from k with respect to coplanar, parallel defects in a regular belt pattern, as given by

$$k = (E' / \iota) k^* \quad (3)$$

Here, $E' = E/(1 - \nu^2)$, where E is Young's modulus, ν is Poisson's ratio, and k* is a dimensionless spring constant, which is uniquely defined by the solid contact area ratio on co-oriented planes, and is not affected by material or pitch ι. Substituting Eq. (3) into Eq. (2), we obtain

$$R = \{(\pi C Z / E' k^*) \iota / \lambda \} / [1+\{ (\pi C Z / E' k^*) \iota / \lambda\}^2]^{0.5} = (S \Lambda) / \{ 1 + (S \Lambda)^2 \}^{0.5} \quad (4)$$

where C is the speed of longitudinal acoustic waves in the material. Thus, S in Eq. (4) is a constant determined by the material, the roughness orientation and the solid contact area ratio α. The reflectivity R in the same sample can vary with the acoustic impulse frequency.

Here, considering the discussion above and the fact that the echo height ratio asymptotically approaches the non-solid contact area ratio (1 – α) at lower wavelengths λ, the following empirically suggested relationship between Λ and H can be proposed.

$$H = R – \alpha (1- e^{\beta\Lambda}) \quad (5)$$

The fine line in Fig. 7 was calculated using the values of S and β that provided the best fit for all the experimental results with different values of α.

Simple Method for Estimating Area with Single Cycle of Received Wave: Some relationship between Λ and H described above was for the echo height of the absolute envelope of reflected full wave as shown in Fig.8. However, some resonance from the non-contact regions is included in the reflection, and this is quite likely to affect the maximum wave magnitude[9]. Here, in order to avoid this effect, the first full-cycle reflected wave is examined alone as the least-distorted waveform. The echo height ratio H_c was defined using the acoustic amplitude, which was determined by the center frequency f_c of the wave, and H_c was used to estimate the area

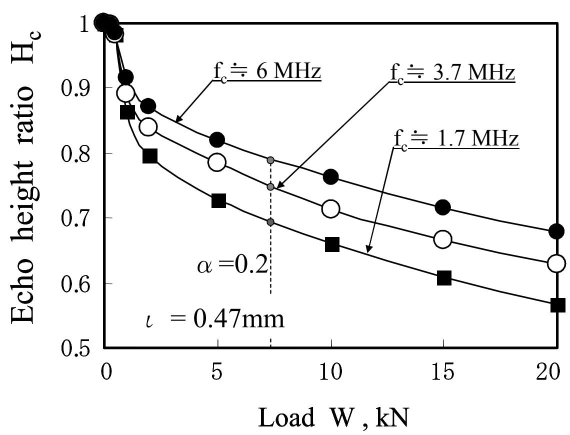


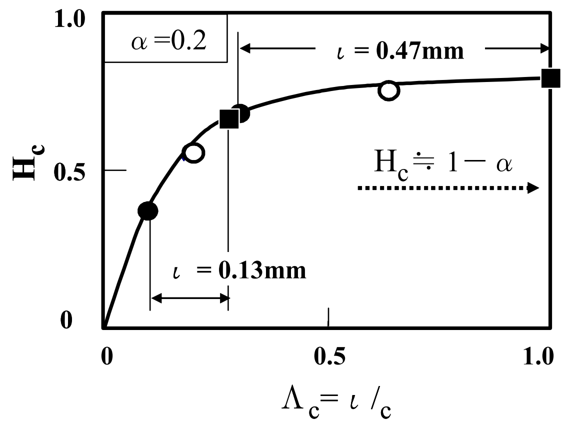
Fig.8 Example of measurement

ratio. Figure 8 shows the relationship between dimensionless pitch $\Lambda_c = \iota/\lambda_c$ and H_c for the two samples examined in Chapter 2, measured with the same procedure.

If the stiffnesses of both faces and acoustic transmission from the contact region are considered, the echo height ratio H_c for acoustic waves injected from a smooth supporting jig surface is given by Eq. (6), based on the definition for reflectivity in Eq. (4):

$$H_c = (1 – \alpha) R_c = (1 – \alpha) (a_s f_c)/ (4 + a_s f_c)^{0.5} \quad (6)$$

Here, $a_s = 2\pi Z A_0/S$ and Z give the acoustic impedance of the acrylic. The value of a_s can be held constant, such that if the echo height H_c is measured with transducers of differing center frequencies f_c, as pointed out earlier, the solid contact area ratio α can be easily estimated using the least-squares method.



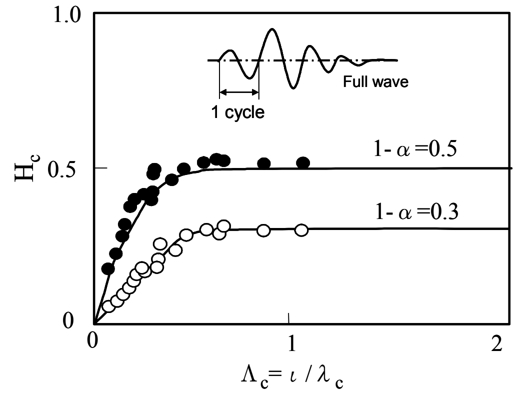
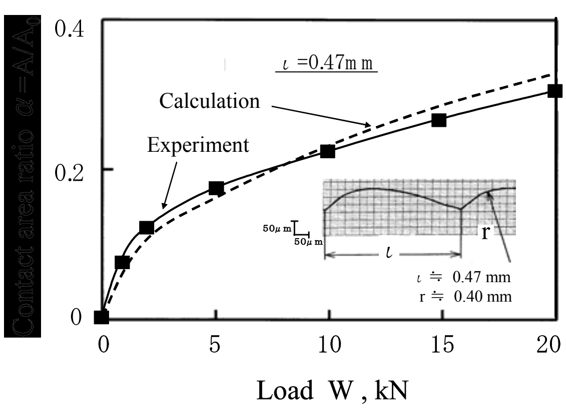


Fig. 9 Relationship between Λ and H_c (α=0.2) **Fig. 10 Relationship between Λ and H_c**

This report has described a method for estimating solid contact area using reflections from a contact region with two-dimensional regular rough surface, which is determined by the solid contact area after truncation. Next, to examine the potential for measurements of the solid contact area in contact between an un-truncated surface and a smooth surface, two samples with two-dimensional roughness (ι = 0.47 mm, r ≅ 0.40 mm; ι = 0.13 mm, r ≅ 0.05 mm) were tested in the same way as described above. The solid area ratio was calculated using the following expression to verify the practicality of the present measurement method. Here, L is the overall length of the ridgeline, given by $L \cong \pi D^2/\iota$, and D is the sample diameter (25 mm).

$$\alpha = A / A_0 = \{ 3.04 (r W)^{0.5} \} / \{ \iota (L E')^{0.5} \} \quad (7)$$

As represented by the data for the ι = 0.47 mm sample in Fig. 9, the echo height ratio H_c gradually diminishes as load W increases. At a certain solid contact area ratio (load), if H_c and frequency are normalized by dimensionless pitch $\Lambda_c = \iota/\lambda_c$, where λ_c is the wavelength at the reflection center frequency f_c (1.7 MHz, 1.72 mm; 3.7 MHz, 0.74 mm; 6 MHz, 0.48 mm) and ι is the pitch of the ridges, we obtain a plot like that shown in Fig. 10. The figure also shows the results for ι = 0.13 mm. As seen in Fig. 8, H_c increases with dimensionless pitch Λ_v and asymptotically approaches the non-contact area ratio (1-α). Figures 11 and 12 present normalized curves for α with respect to load W. The dashed line represents the solid contact area ratio as predicted by Eq. (7) using actual material properties and sample shape, and can be seen to match the experimentally observed data quite well.



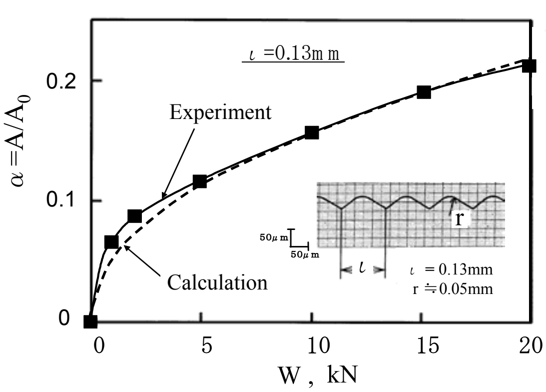


Fig.11 Estimated result (ι=0.47mm) **Fig.12 Estimated result (ι=0.13mm)**

Conclusions: The influence of asperity (ridge) pitch and acoustic pulse wavelength on the characteristics of reflection of acoustic pulses from the contact region between two bodies in dry, stationary contact was investigated to examine the potential of echo height ratio as a parameter for ultrasonic measurements of solid contact area. A simple method of quantitatively measuring the solid contact area on an arbitrary surface of unknown contact asperity pitch was investigated. The results obtained are summarized as follows.

1) The echo height ratio H is determined by the pitch ι of ridges in the solid contact region and the acoustic wavelength λ, as well as by the solid contact area ratio $\alpha = A/A_0$.
2) If the fraction $\Lambda = \iota/\lambda$ is used, however, H is uniquely determined by α.
3) If α is used as a parameter for H, the H-Λ relation exhibits a slight peak in the region Λ = 0.3–0.5.
4) This curve is affected by quasi-static stress in the ultrasonic medium. The curve consists of a region below Λ = 0.3–0.5, which is dominated by the stiffness of the surface, a region at $\Lambda > 1.5$, where H approaches $(1 - \alpha)$, and a transition region between the two.
5) The solid contact area ratio can be directly calculated from the echo height ratio in the $\Lambda > 1.5$ region.
6) It is possible to infer the solid contact area ratio in the general $\Lambda < 1.5$ region by observing the variation in the echo height ratio due to changes in frequency and the influence of quasi-static stress.
7) The solid contact area ratio α estimated using the echo height ratio H_c of the center frequency f_c of the reflected acoustic signal and the reflectivity characteristics as influenced by the stiffnesses of the two surfaces is nearly identical to the value of α calculated from actual measurements of the asperity radius. This confirms the validity of the proposed measurement method.

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