Quantitative Evaluation of the Flaw Echo of Railway Axles in Consideration of Contact Pressure with a Wheel

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For railway axles, the wheel seat is periodically inspected by ultrasonic testing. When the ultrasonic axle inspection is performed while the wheels are mounted, the flaw echo height varies depending on the fitting condition. When the inspection is performed on an in-service axle, the echo height also varies under the influence of the bending load acting on the axle due to the car weight. In this study, the variation in echo height due to the contact pressure with a wheel was quantitatively evaluated by simulation of ultrasonic propagation. Moreover, the echo-height variation during cyclic rotating bending in a full-sized wheelset was investigated experimentally by studying variation in normal stiffness at the axle-wheel interface.

Keywords: axle, ultrasonic testing, flaw echo, contact pressure, interfacial stiffness

1. Introduction

In the periodic inspection of railway axles, the wheel seats (the fitting seats for wheels) are inspected by means of ultrasonic testing with mainly shear-wave angle beams thus ensuring axle safety [1]. When the ultrasonic testing is performed while the wheels are mounted, however, the flaw echo height varies due to fluctuation in the axle-wheel contact pressure depending on their fitting condition. Moreover, in regular Shinkansen (Japanese high-speed railway line) car inspections, the ultrasonic testing of axles is usually performed under in-service conditions where the car is mounted with all the parts required for normal operation. In this case, the contact condition with a wheel varies under the influence of the bending load acting on the axle due to the car weight, which causes a variation in echo height. The influence of the contact condition with a wheel on the ultrasonic axle inspection is comprehended qualitatively as mentioned above. Marshall et al [2] reported on the quantitative evaluation of the contact pressure distribution at the wheel seat of a hollow axle measured by the normal longitudinal ultrasound. However, there exists no report which deals with these aspects from the viewpoint of ultrasonic axle inspection with shear-wave angle beams.

In this study, the variation in echo height due to the flaw depth and the contact pressure with a wheel was quantitatively evaluated by simulating ultrasound propagation with a model for expressing the axle-wheel fitting interface. A cyclic rotating bending test was performed for a full-sized wheelset presenting flaws in the fitting seats. The variation in flaw echo due to the contact condition with a wheel and the bending load acting on the axle was investigated experimentally by comparing it with variation in normal stiffness at the interface.

2. Modeling of axle-wheel fitting interface

2.1 Spring interface model

When an axle is press-fitted with a wheel, the inner bore of the wheel is machined with a certain roughness and with a smaller diameter than that of the wheel seat to have a designated interference against the axle. From a microscopic perspective, therefore, the axle-wheel fitting interface involves two surfaces with respective roughnesses, which come into contact under a certain contact pressure due to the interference, shown in Fig. 1(a). This condition is modeled approximately by the spring interface [3] shown in Fig. 1(b) with two kinds of interfacial stiffnesses, normal stiffness $K_N$ and tangential stiffness $K_T$. These stiffnesses correspond to the increment of the normal or shear stress generated when the relative distance between the axle and the wheel varies by a unit length in each direction. As both of the axle and the wheel are manufactured from carbon steel, we consider, in the following, that both of them are of an isotropic material defined by the Lamé constants of $\lambda$ and $\mu$, which means that the density $\rho$ and the longitudinal and shear wave velocity, $c_L$ and $c_T$, are identical for both.

![Fig. 1 Spring interface model](image-url)
When the longitudinal or shear wave with an angular frequency \( \omega = 2\pi f \) (frequency) is incident perpendicularly to the spring interface from the axle to the wheel, the relation between the interfacial stiffness and the reflection coefficient of ultrasound is expressed as

\[
K_N = \frac{\rho c E}{2} \frac{1}{\sqrt{R_L^2 - 1}}
\]

(1)

\[
K_T = \frac{\rho c E}{2} \frac{1}{\sqrt{R_T^2 - 1}}
\]

(2)

where \( R_L \) and \( R_T \) are the reflection coefficients of longitudinal and shear waves for the normal incidence, respectively.

2.2 Equivalent model with a periodically cracked interface

The above-mentioned spring interface needs a model with spring elements corresponding to the interfacial stiffnesses for calculating ultrasound propagation with a finite element method. Therefore, a model was applied in this study with a periodically cracked interface shown in Fig. 2.

It is known that the behavior at the interface in this model is equivalent to the spring interface from the axle to the wheel, the reflection between the interfacial stiffness and the reflection coefficient \( R \) against the bonding ratio \( w/s \) obtained by (1) and (3) were as shown in Fig. 3. \( K_N \) increased and \( R_L \) decreased with the increase in \( w/s \).

3. Evaluation of flaws in the wheel seat through ultrasound simulation

3.1 Simulation objectives

When the wheel seat is inspected by a shear-wave angle beam as shown in Fig. 4, the ultrasound transmitted from an angle probe is reflected both at the axle-wheel interface and the flaw face and some ultrasound is transmitted through them. The reflection coefficients at these faces significantly influence the received flaw echo height. Therefore, the echo-height variation due to the flaw depth and the contact pressure at the axle-wheel interface was calculated by ultrasound simulation.

![Fig. 4 Reflection and transmission of ultrasound at the flaw in the wheel seat in the case of angle beam inspection](image)

3.2 Relation between contact pressure and interfacial stiffness

In order to identify the relation between the contact pressure and the interfacial stiffness at the axle-wheel interface, an experiment was performed using a miniature wheelset test piece, illustrated in Fig. 5. The diameter of the wheel seat was 57 mm and the interference was adjusted to generate a contact pressure of approximately 85 MPa similar to that of a full-sized wheelset. At first, a longitudinal-wave normal probe with a frequency of 5 MHz was placed on the outer surface of the wheel as shown in Fig. 5(a), and then the amplitude spectrum of the reflected
wave at the axle-wheel interface, $h_{RL1}$, was measured. Next, in the condition of a wheel alone as shown in Fig. 5(b), the amplitude spectrum $h_{RL2}$ was measured in the same way. The reflection coefficient of the longitudinal wave $R_L$ was calculated by the ratio of amplitude spectra as follows:

$$R_L = \frac{h_{RL1}}{h_{RL2}}$$  \hspace{1cm} (4)

Similarly, a shear-wave normal probe with a frequency of 5 MHz was placed on the wheel to make the vibration direction parallel to the central axis of the axle, and then the reflection coefficient of the shear wave $R_T$ was calculated by the amplitude spectra $h_{RT1}$ and $h_{RT2}$ measured in the conditions illustrated in Fig. 5(a) and (b) as follows:

$$R_T = \frac{h_{RT1}}{h_{RT2}}$$  \hspace{1cm} (5)

By substituting $R_L$ into (1) and $R_T$ into (2) which were obtained by the measurement, the normal stiffness $K_N = 2.11$ MPa/nm and the tangential stiffness $K_T = 0.570$ MPa/nm were identified. Provided that the contact pressure at the axle-wheel interface $p$ (MPa) is proportional to $K_N$ (MPa/nm) [2], the relationship of $p = 40.3K_N$ was derived as $K_N$ was 2.11 MPa/nm for $p$ of 85 MPa.

### 3.3 Calculation model

Figure 6 shows the two-dimensional calculation model, corresponding to the conditions described in Section 4 that the wheel seat of a full-sized wheelset was inspected from the axle bore by an angle probe. The material of the probe was acrylic resin and that of the axle and the wheel was steel. The displacement in the direction perpendicular to the paper surface was fixed. The shape of all elements was the identical square with an area length $d$ of 0.04 mm which was approximately 1/16 of the shear wave length $\lambda_T$ of 0.646 mm. The number of elements was approximately 7.7 million. The axle-wheel fitting interface was modeled by the periodically cracked interface mentioned in Section 2.2 with a fixed width of periodic boundary $s$ of 0.32 mm. The bonding ratio $w/s$ was set at the four values of 0, 0.25, 0.5 and 0.75 to change the interfacial stiffness in the model. The flaw depth in the wheel seat $a$ was changed by the four values of 1, 2, 3 and 5 mm for respective models with each $w/s$.

The displacement amplitude of the received wave corresponding to the echo height was calculated for the shear-wave angle beam inspection with a frequency of 5 MHz and a refraction angle of $45^\circ$. The software ComWAVE Ver. 5.0.1 provided by ITOCHU Techno-Solutions Corporation was used for the ultrasound simulation. Prior to the calculation, the respective ratios of the reflected waves at $w/s = 0.25, 0.5$ and 0.75 to that at the free surface of $w/s = 0$ were
calculated for both longitudinal and shear waves which were incident perpendicular to the interface by the use of a two-dimensional model with the width of one periodic boundary. The ratios corresponded to the reflection coefficients $R_{L}$ and $R_{T}$, and the interfacial stiffnesses expressed in each calculation model were identified by (1) and (2).

Table 1 shows the interfacial stiffnesses, $K_{N}$ and $K_{T}$, and the contact pressure which was converted by the $p$-$K_{N}$ equation shown in Section 3.2.

### 3.4 Influence of flaw depth and contact pressure on echo height

Figure 7(a) shows the distribution of received echo heights against the variation in flaw depth $a$ for respective models with each bonding ratio of $w/s$. The scale in vertical axis was selected arbitrarily depending on the amplitude of the incident waves. For any case of $w/s$ corresponding to the contact pressure, the echo heights were approximately proportional to the flaw depths for flaws shallower than 2 mm. However, the increasing rate of the echo height decreased for those deeper than that. The echo heights fell as a whole with the increase in $w/s$.

The ratios of echo heights at respective $w/s$ to that at $w/s = 0$ were calculated for respective models with each flaw depth of $a$. Figure 7(b) shows the distribution of the echo height ratio against the contact pressure $p$ to which $w/s$ was converted by Table 1. For any flaw depth in the wheel seat, the echo height decreased by the effect of the contact pressure. At a contact pressure of 50 MPa, the echo height decreased by approximately half of that at no contact pressure. For the contact pressure higher than that, the echo height was approximately inversely proportional to the contact pressure. As described above, we consider that the contact pressure at the axle-wheel fitting interface strongly influences the flaw echo heights.

### 4. Influence of cyclic rotating bending loads on the fitting interface

#### 4.1 Cyclic rotating bending test for full-sized wheelset

#### 4.1.1 Test method

The above-mentioned findings on the relation between the contact pressure and interfacial stiffnesses are to be applied to the test results of a full-sized wheelset [5]. In the following, the influence of the cyclic rotating bending load acting on the running axle on the fitting interface is evaluated.

Figure 8 shows a full-sized test wheelset equipped with a hollow axle with a bore diameter of 40 mm. As shown in Fig. 9, four rectangular flaws A to D were machined on the wheel seat in one side of the test axle by electric discharge machining. Figure 10 shows a schematic view of the ultrasonic axle testing equipment. Two ultrasonic angle probes with a nominal frequency of 5 MHz and a nominal refraction angle of 45˚ were installed in the probe head. This head was inserted from the axle end and each probe transmitted the ultrasound obliquely forward or backward to detect flaws.

The cyclic rotating bending was applied to the axle by using a full-sized wheelset fatigue testing machine. The loads were applied to the positions indicated in Fig. 8. First, a nominal bending stress at the wheel seat (referred to as the test stress) of approximately 40 MPa was applied...
and the wheelset was rotated by $5 \times 10^7$ cycles. After that, the test stress was increased to 60 MPa and the wheelset was rotated by additional $3 \times 10^7$ cycles. The ultrasonic testing of the flaws was performed at the stages of I to V in the following. At stages II to IV, the flaw echo was measured with the bending moment applied to the axle:

I. The no-load condition of the as-manufactured test wheelset,

II. Before the rotating bending at a test stress of 40 MPa,

III. The state with a test stress increased to 60 MPa after the test at 40 MPa,

IV. After the rotating bending at a test stress of 60 MPa,

V. The no-load condition of the test axle alone after disassembling the wheels and so on.

In the ultrasonic testing, the test wheelset was halted to set flaw D almost vertically upward ($0^\circ$) and downward ($180^\circ$). The echo height of each flaw was measured by forward and backward ultrasound. To eliminate the influences of the contact condition of the probe and the temperature change, the measured echo heights were normalized by that of the flaw in the axle body with a depth of 1 mm and a length of 10 mm. The main test results of the forward ultrasound are described below.

4.1.2 Test results of flaw echoes

Figure 11 shows the echo heights of each flaw in a decibel scale measured by the forward ultrasound when flaw D was set vertically upward and downward. The transition from stage I to II yielded the echo-height variation only
within ±1 dB for each flaw. The echo heights tended to
decrease with the progression from stage II to III and then
slightly increase at stage IV. The variation in echo height
was most significant for flaw D nearest to the fitting edge.

4.2 Variation in interfacial stiffnesses according to
cyclic rotating bending

The variation in contact condition at the fitting inter-
face according to the cyclic rotating bending was evaluated
here by the local interfacial stiffness in the vicinity of each
flaw. We assumed that the flaw echoes at stage V were
obtained by the free surface reflection with $R_T = 1$. In this
assumption, the shear wave reflection coefficient $R_T$ was
obtained by the ratio of each echo height at stages I to IV
to that of stage V. Consequently, the normal stiffness $K_N$
was calculated by the equation for the oblique incidence of
shear wave with an angle of 45˚ [6]:

$$R_T = \frac{1}{\sqrt{1 + \left(\frac{\sqrt{2}K_N}{\omega \rho C_T}\right)^2}}$$  (6)

For flaws A and C which were located in the vicinity of
the neutral plane of the axle in the measurement of echo
heights and hardly affected by the bending moment, the
variation in $K_N$ is shown in Fig. 12, which was converted
from the echo-height ratio for each flaw in Fig. 11(a) and (b)
and then averaged. The normal stiffness hardly changed
with the progression from stage I to II and increased with
the progression from stage II to III, and then slightly de-
creased at stage IV. The normal stiffness in the vicinity of
flaw A was higher as a whole than that in the vicinity of
flaw C.

The two surfaces, each of which had a certain periodic
asperity, were under the condition where too many projec-
tions were in contact from interference in stages I and II,
which yielded a relatively lower normal stiffness. After
that, the normal stiffness increased with the progression
from stage II to III as the two surfaces fitted better and the
real contact area increased due to the initial wear by the
fretting from rotating bending cycles. Then, further devel-
oped wear at the fitting interface generated a gap, which
was considered to be responsible for the decrease in normal
stiffness which progressed between stage III and IV. As
flaw A was located farther from the fitting edge than flaw
C and its position was more unsusceptible to the fretting,
the normal stiffness in the vicinity of flaw A was consid-
ered to be higher than that in the vicinity of flaw C. These
conditions are shown schematically in Fig. 13.

4.3 Influence of bending moment on flaw echoes

Figure 14 shows the difference in echo height due to
the change in stopping positions by 180˚, which was calcu-
lated from Figs. 11(a) and (b) for each flaw, for stages II to
IV. Positive values in this figure indicate that the flaw echo
height was greater when flaw D was set vertically upward.
The echo-height differences of all flaws were small at stage
II. Both of flaws B and D were measured when they were
set farthest from the neutral plane. Only flaw D showed a
marked variation in echo-height difference as testing stages progressed, reaching +6.6 dB at stage IV.

The cause for this was considered to be as follows: at first, the axle and the wheel were under the condition where too many projections were in contact at stage II as shown in Fig. 13(a). As the change in the real contact area due to the loading of bending moment was marginal, the echo-height difference was also small. Subsequently, the conformability and wear at the fitting interface developed. Finally, as shown in Fig. 15, the fitting interface in the vicinity of flaw D varied between the condition of being in contact and that of having a gap depending on the stopping position of the wheelset, which yielded a marked echo-height difference for flaw D. Meanwhile, there was no marked echo-height difference for flaw B as the wear had not developed to such an extent that a gap was generated in the vicinity of the flaw.

5. Relevance to ultrasonic testing of axles

In this study, the influence of the fitting condition on flaw echoes was evaluated by using a wheelset equipped with a hollow axle with a bore diameter of 40 mm. Similar effects are expected to be found for hollow axles for Shinkansen cars with a bore diameter of 60 mm and solid axles. For the axles in service, the axle-wheel fitting interface fits better after a certain period of train operation from the time of manufacture or the exchange of wheels. This may cause the decrease in echo heights in the ultrasonic testing compared to the same flaws in a newly manufactured wheelset. For the wheelsets which have been in operation for a longer period of time, however, higher flaw echoes may be detected due to the gap generated by wear at the interface.

Ultrasonic testing of Shinkansen axles while in-service is not subject to the same level of stress used in the tests for this study, i.e. 60 MPa. Nonetheless the flaw echo height may vary by several decibels because of the bending moment due to the car weight.

A model wheelset, in which a new axle is assembled
with several machined artificial flaws, is often used for calibrating sensitivity for ultrasonic axle inspection. In order to avoid oversight and underestimation of flaws, several methods are effective. For example, the threshold levels for flaw detection are to be changed according to the interference of the axle against the wheel or the period of train operation. When a flaw is detected during an in-service ultrasonic examination, the inspection should be performed again by partially lifting the wheelset off the rail. These methods can help increase axle safety.

6. Conclusions

The results obtained in this study can be summarized as follows.

The influence of the flaw depth at the wheel seat and the contact pressure with a wheel on echo height was evaluated by the ultrasound simulation. We clarified that the echo heights were approximately proportional to the flaw depths for flaws shallower than 2 mm and that the echo height at a contact pressure of 50 MPa decreased by approximately half compared to when there was no contact pressure.

In the cyclic rotating bending test for a full-sized wheelset with flaws in the fitting seats, the echo height varied by several decibels due to the change in axle-wheel contact conditions or because of the circumferential flaw position. These results were explained by the change in normal stiffness at the interface.

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