ON THE ACCURACY IMPROVEMENT IN ULTRASONIC INSPECTION BY USING COMPUTER GRAPHICS AND WAVEFORM ANALYSIS

Noboru SUGAWARA*, Toshiyuki OSHIMA**,
Shuichi MIKAMI*** and Shinya SUGIURA****

The C-scan images of defects made by drilled holes with different types are obtained and the effect of length and inclination of drilled holes on the images are discussed in this paper. The artificial cylindrical defect of diameter 1mm and 2mm were made in a steel plate specimen of 9mm thick and 3D images of these defects are obtained by using a graphic software on a workstation from the maximum amplitude and path length data of received waves. In the detail waveform analysis of boundary and bottom echo the method to get more accurate size of defect are shown. And in order to apply C-scan ultrasonic test to a field inspection the effect of surface roughness and thickness of specimen on their images are analyzed and the modified immersion method to use a small water bag between a probe and a specimen are proposed.
Keywords : ultrasonic inspection, computer graphics, 3D image, NDE

1. INTRODUCTION

When we diagnose the structural integrity of a steel member in service and evaluate its remaining life time, we need to improve analyzing method to get the accurate information of a internal defect of a member. And by the recent demand for high level quality control of welding of steel joint the accuracy improvement of defect detection in the image display became essential in nondestructive evaluation (NDE)[1)–3)]. So far the defect information obtained by an ultrasonic test is displayed in several ways and A-scan and B-scan displays are commonly used in a field inspection and C-scan display is mostly used in laboratory test of the steel structural member[4),5)].

In this study we made the different types of artificial defects by drilled holes in a steel plate specimen to be observed by an ultrasonic scanning pulse echo test. And the several effects of measurement condition on the display image are obtained by this experimental analysis[6),7)]. The artificial drilled holes with diameter 1mm and 2mm are made with different lengths and inclinations and the graphic images are compared among these cases. 3D images of these defect are obtained by a graphic software[8)] on a workstation by using the maximum amplitude data of boundary and bottom echo and path length data by which we find from where the incident wave returned back. And in order to apply the C-scope immersion method of ultrasonic test to a field inspection, the effects of surface roughness and the thickness of specimen are analyzed, and also the simple method not to use a water tank but to use a small water bag between a probe and a specimen are used to get the same C-scan image of immersion test. The accurate defect size obtained by the ratio of the maximum amplitudes between the boundary echo and bottom echo are shown in the detail waveform analysis of the reflection wave.

2. MEASUREMENT SYSTEM

The measurement system employed in this study is shown in **Fig.1**. This system of immersion type ultrasonic testing can be illustrated by the several parts of subsystem and these subsystems are
(1) Image display system
  a) ultrasonic transducer
  b) automatic scanning controller
  c) amplitude sampler of ultrasonic wave
  d) image display computer
(2) Ultrasonic wave recorder system
Main functions of this system are automatic scanning control, ultrasonic acquisition and image display and their datails are as follows :
  1) Ultrasonic transducer (normal transducer of focussed type) of immersion testing
    a) frequency of transducer
        5MHz   10MHz   25MHz
    b) approximate focal length in water
        50mm   40mm   20mm
  2) Automatic scanning control system

 * Member of JSCE, Associate Professor, Department of Civil Engineering, Kitami Institute of Techonology
   (165 Koen-cho, Kitami, Hokkaido)
 ** Member of JSCE, Dr.Eng., Professor, Department of Development Engineering, Kitami Institute of Techonology
 *** Member of JSCE, Research Associate, Department of Development Engineering, Kitami Institute of Techonology
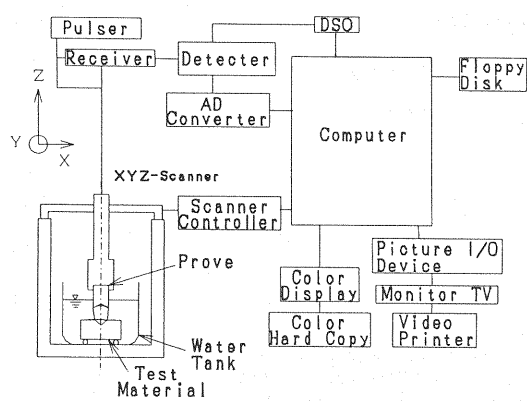 **** Member of JSCE, Research Engineer, Konoikegumi Corporation

Fig.1 Measurement system

Table 1 Specimens

Type I	$\phi(°)$	h (mm)	Type II	$\phi(°)$	h (mm)
A		5	J		5
B	90	3	K	90	3
C		2	L		2
D		5			
E	75	3	Type I		
F		2			
G		5			
H	60	3	Type II		
I		2			

(3D rectangular coordinates)
a) scanning range (mm)
     500(W) × 600(L) × 250(D)
b) scanning pitch (variable, mm) 0.05~9.95
c) scanning speed 10~150mm/sec
     (automatically given correspond to scan-
     ning pitch)
3) Image display system (C-scope)
a) 256 gradations of monochrome between
     white and black
b) 16 gradations of color level
4) Ultrasonic wave recorder system
     (Digital storage oscilloscope)
a) sampling speed
        500 Mega samples per second
b) resolution of amplitude 10 bit
c) frequency range up to 300MHz
d) option for FFT
The sampling gate of time axis is set correspond
to the thickness of specimen to receive first
boundary echo from a defect and bottom echo.
Data of maximum amplitude of each echo waves
which passed above sampling gate are obtained as a
digital value of a voltage by a translation of
analogue signal. We get its changes of the
maximum amplitude correspond to the shape and
thickness of a defect. Comparison of this digital
voltage data with the reference voltage gives us
image data to represent the 2D shape of defect on
the screen. Ultrasonic wave recorder system can
get the whole reflection waves that passed above
mentioned time gate as 4096 data of digital values
for every wave and display the spectrum of the
detected waves by FFT.

3. DETECTED IMAGE OF DEFECT SHAPE

When we detect a defect shape by using
ultrasonic testing, the accuracy of image data of a
detected defect depends upon the resolvability of
positioning and inclination of transducer during the
measurement. It is important to employ a good
system to improve the accuracy. What we discuss
here is to analyze ;
a) the effect of ultrasonic wave scattering at the
     boundary of a defect and the coupling effect
     of two close defects on the image
b) the effect of depth and inclination of drilled
     holes in the specimen
c) the effect of frequency of transducer on the
     image data
After the comparison of resolution of image data
obtained by three transducer of different natural
frequencies we decided to use the transducer
mostly with 10MHz frequency in this research.
(1) **Specimen and measurement**
In the steel plate specimen with 9mm thick
twelve artificial defects of different types are made
by drilled holes as shown in **Table 1.** Among them
there are three types of depth h as 5mm, 3mm,
2mm and three types of inclinations ϕ as 90°, 75°,
60° of drilled holes, respectively. And the dia-
meters of drilled holes are 2mm and 1mm as shown
in **Table 1** and two close holes of diameter 1mm at
2mm distant are used to get the coupling effect of
ultrasonic scattering on the image of defect.
The kinds of the specimen for coupling effect are
named by specimen J, K, L with different depth as
5mm, 3mm, 2mm as shown in **Table 1**, respective-
ly. Reflection waves from the defect are measured
by using a line scanning along with a distinct line to
across the C-scan image of defect. They are
discussed later.
Data of maximum amplitudes of bottom echo
and boundary echo passed through the time gate
for each scanning point are used to display a C-scan
image on the screen. This set of data for C-scan
image is called "maximum amplitude data" in this
paper. Data of path length between incident point
and where the detected boundary echo returned
back are also used to find out the depth of the
defect. This set of data of path length is called
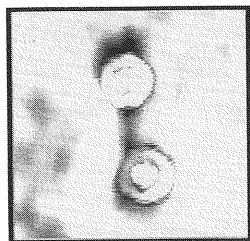"path length data" and obtained at each scanning
point.

Fig.2 C-scan image of specimen K
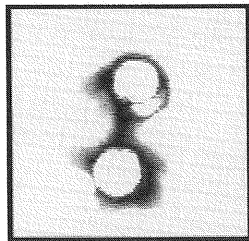(6×6 mm, pitch 0.05 mm, scale ⊢———⊣0.8 mm)

Fig.3 C-scan image of specimen J
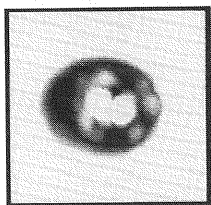(6×6 mm, pitch 0.05 mm, scale ⊢———⊣0.8 mm)

Fig.4 C-scan image of specimen D
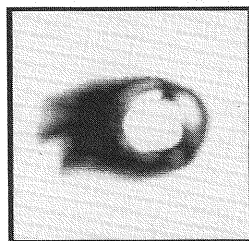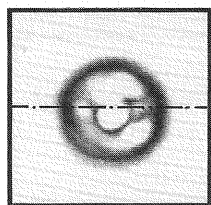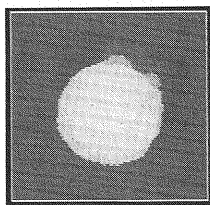(5×5 mm, pitch 0.05 mm, scale ⊢———⊣0.8 mm)

Fig.5 C-scan image of specimen G
(6×6 mm, pitch 0.05 mm, scale ⊢———⊣0.8 mm)

(a) Maximum amplitude data

(b) Path length data

Fig.6 Images of maximum amplitude data and path length data for specimen A (5×5 mm, pitch 0.05 mm, scale ⊢———⊣0.8 mm)

(2) Results of display image

The C-scan image of defect K and J with different depth obtained by using the transducer with 25MHz are shown in **Fig.2** and **Fig.3**, respectively. The tip shapes of drilled holes are well detected and the resolution of image for defect J is rather poor than that for defect K. The focal point of the ultrasonic waves is adjusted around at the tip of drilled hole in this measurement. If the depth of drilled hole is deep, that is, the distance between the defect tip and bottom of plate is large, the scattering effect of ultrasonic wave on the display image of the defect becomes to be larger than the others. This behavior of wave scattering and the decrease of resolution is considered somewhat like that the dim resolution of a photo is obtained by a insufficient exposure depth of a camera.

The coupling effect of two close defects of small size does not effect on their image in this case. By the comparison of defect image with different frequencies of transducers it is considered that a good result of display image of defect shape is obtained by the transducer with higher frequency. However the focal length of the transducer with high frequency is so small that the transducer with 10MHz is considered to be suitable to use for the inspection of steel structure. The effect of shape and inclination of the defect on the display image is not observed in this case and good resolutions of the images are obtained for each case of defect types. The display images for the defect D and G of inclined drilled holes are shown in **Fig.4** and **Fig.5**, respectively. By the comparison of the image results between the defect A as shown in **Fig.6**(a) and the defect D and G with different inclinations of the drilled holes, it is seen that the amplitude of boundary echo becomes small. However good resolution of display image for each defect types are obtained by this system of measurement. And by the comparison of the maximum amplitude data with the path length data as shown in **Fig.6**(a), (b) for defect A, the accurate depth of the defect is given. It is discussed in the next chapter by using computer graphics.

4. 3D DISPLAY OF DEFECT SHAPE BY MAXIMUM AMPLITUDE DATA AND PATH LENGTH DATA

As mentioned before, by using ultrasonic inspection system we can obtain the maximum amplitude data which represent the distribution of maximum amplitude of echo waves reflected from the bottom of the plate or boundary of the defect and the path length data which represent from where the incident wave returned back. And with these data we can get the C-scan images of maximum amplitude and path length with 256 grades of color display on 2D rectangular coordinate.

In this chapter 3D representation of maximum amplitude data by using a computer graphics (CG) software on a workstation (WS) is shown. In this analysis the values of 256 color grades correspond to the amplitude which are on the 2D plane of scanning range are taken in the vertical coordinate perpendicular to the above 2D plane. And the path length data are used like filtering of the boundary echo waves by which we can pass the boundary echo waves through to separate from the bottom echoes within the scanning range. By this filtering technique we can get the clear 3D images of maximum amplitude data by representing the clear
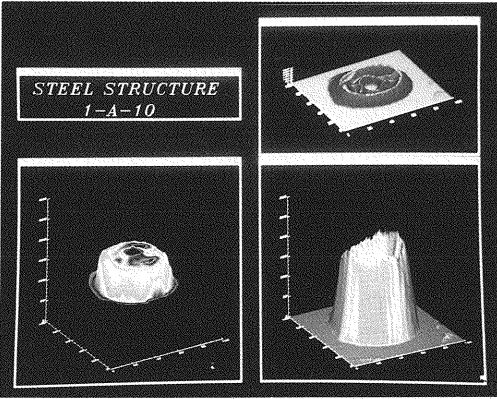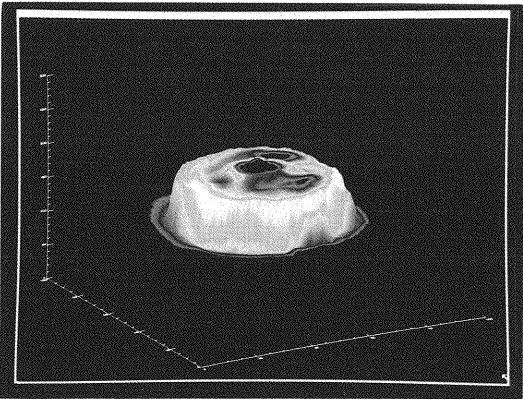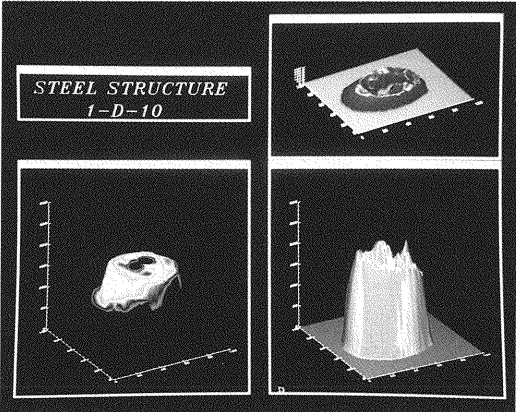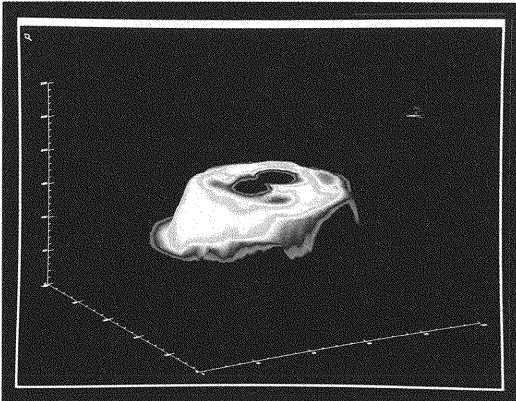
(a)   (b)
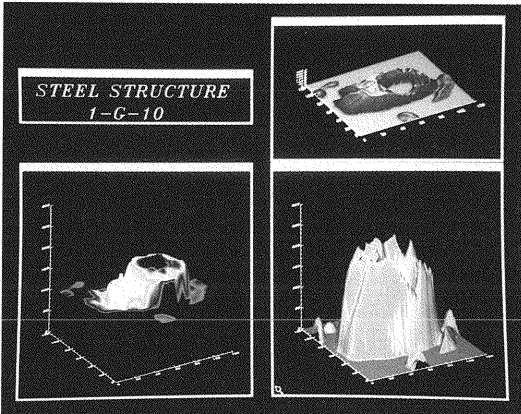
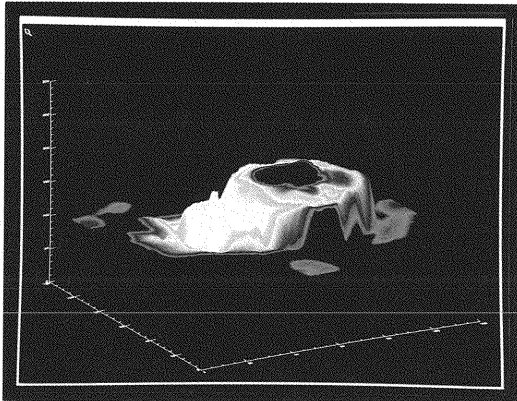**Fig.7** 3D images of specimen A

(a)   (b)

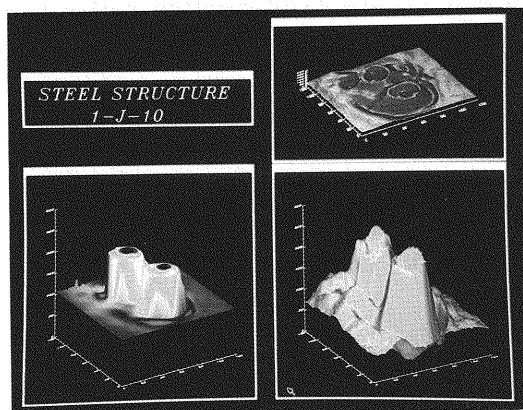**Fig.8** 3D images of specimen D


(a)   (b)

Fig.9 3D images of specimen G

boundary of small defect.

In **Fig.7**(a) three different 3D images of defect type A as listed in **Table 1** are shown. In the lower picture of right hand side in **Fig.7**(a), the above mentioned 3D representation of the maximum amplitude data by converting the 256 color grades values to the vertical coordinate values within the scanning range is shown by using CG software on the WS display. In the upper picture of right hand side in **Fig.7**(a) the different representation of the
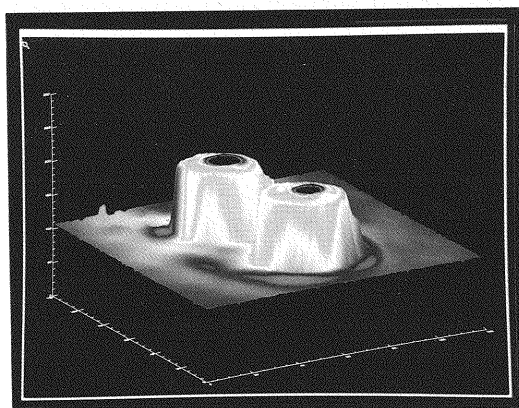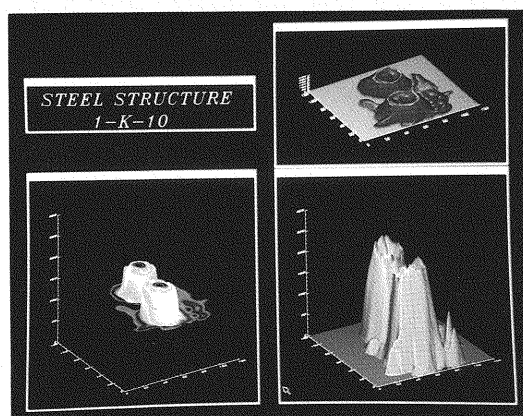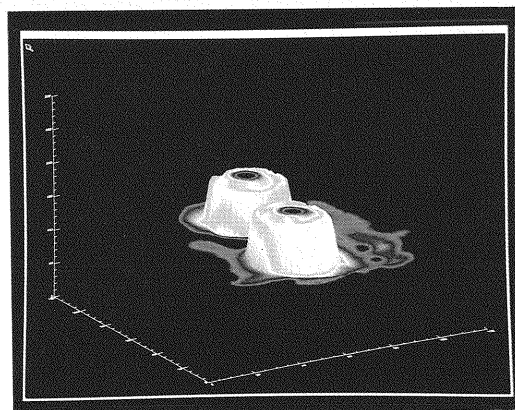
Fig.10   3D images of specimen J

Fig.11   3D images of specimen K
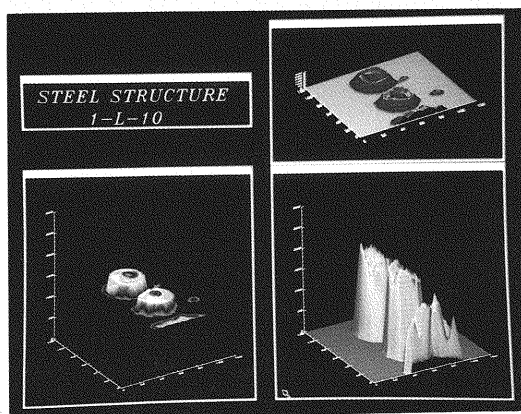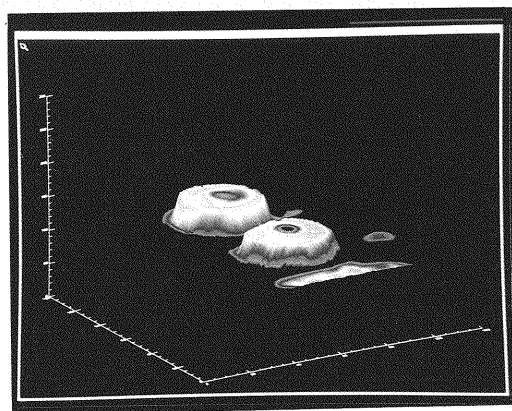
Fig.12   3D images of specimen L

same 3D image as mentioned above is shown by changing the location of view point and the scale of vertical coordinate on CG software. By this picture we can find out the detailed undulation of small defect tip by clear image. In the lower picture of left hand side in **Fig.7**(a) only the 3D image of a defect shape is shown in the dark background by using the path length data to pass only the boundary echo values by an above mentioned filtering technique.

In **Fig.7**(b) the enlarged picture of the same defect as shown in **Fig.7**(a) is shown. And by using 3D rotation procedure on CG software we can rotate the 3D image of the defect on the display of WS we can understand the whole shape of a small defect by 3D representation. Similarly in **Fig.8**(a), (b), and **Fig.9**(a), (b), the 3D images of defect types D and G as shown in **Table 1** are shown, respectively. By these pictures the effect of inclination of drilled holes on the 3D images are clearly obtained. And in **Fig.10**(a), (b), **Fig.11**(a), (b), and **Fig.12**(a), (b), the 3D images of the defect types J, K and L are shown, respectively. The depths of the two close drilled holes are smaller in the order of J, K and L as 5mm, 3mm and 2mm, respectively. By using this CG technique to obtain 3D images of defects we can find out the detailed structure of a defect and thus evaluate the accurate strength of a material. It is called a "D-scope display" of a defect correspond to the A-scope, B-scope and C-scope display.

5. APPLICATION OF C-SCAN DISPLAY TO THE FIELD INSPECTION

(1) Effect of surface roughness on the C-scan image analysis

In order to investigate the scattering effect due to surface roughness of a specimen on the accuracy of the defect detection, the grains of sand are spread on the steel plate of 6mm thick and the artificial surface roughness with small amplitude is made on the upper surface of the specimen. The drilled hole of diameter 4mm and length 3mm are made on the lower surface of the specimen.

The grain sizes of sand are 0.15mm, 0.2mm and 0.3mm for three different specimens, respectively, and the power spectrum of surface roughness in the case of grain size 0.3mm are shown in **Fig.13**. This results obtained by the equipment for surface roughness which can scan on the area of artificial defect by 0.1mm pitch. The amplitudes of surface roughness of 101 points over the area of 10mm × 10mm(100mm^2) are obtained in this case by 11 lines of equal distance and analyzed by FFT spectrum software. The result shown in **Fig.13** is the average power spectrum of surface roughness by the above 11 lines of equal distance over the defect.
The straight line is given by

$$S = a\Omega^{-n} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where　S＝power spectrum of surface roughness
　　　　a, n＝parameters for surface roughness
　　　　Ω＝frequency of surface roughness
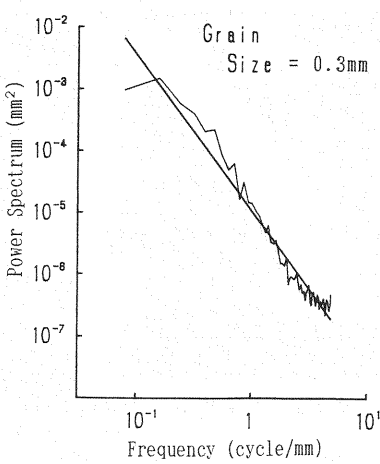The results of parameters a, n for three cases of surface roughness are shown in **Table 2**. The defect

Fig.13 Power spectrum of surface roughness

Table 2 Results of parameters a, n

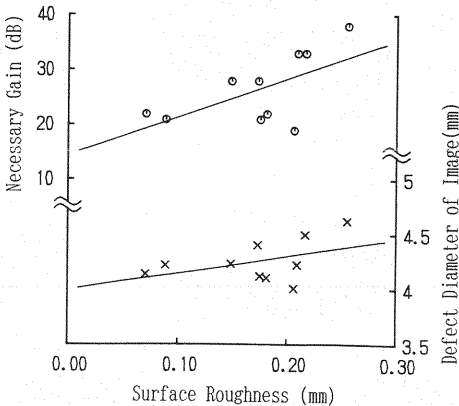| Grain size (mm)	a(10^{-6})	n
0.15	1~4	2.3
0.20	5~10	2.4
0.30	7~13	2.3

Fig.14 Scattering effect by sand on steel surface (Grain size is 0.3 mm)

diameters on the detected images of drilled hole of real diameter 4mm and necessary gain values of amplifier of the system in the case of grain size of 0.3mm, are shown in **Fig.14**. The abscissa of this figure is root mean square of surface roughness. The values shown by the mark × and scaled by the ordinate of right hand side correspond to the results of detected diameters of drilled hole. If the surface roughness becomes large, we need to choose the large gain value for amplification of the measurement. However when we use large amplification, we loose SN ratio at the measurement.
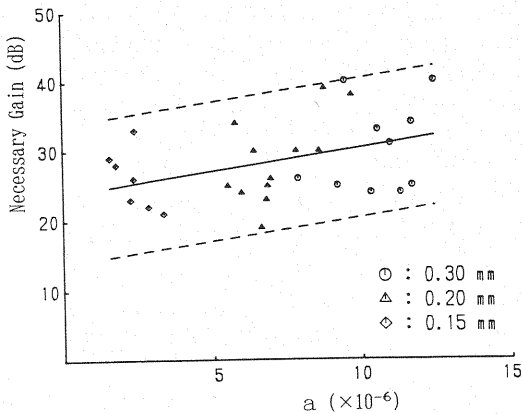
Fig.15   Relation of necessary gain and parameter a
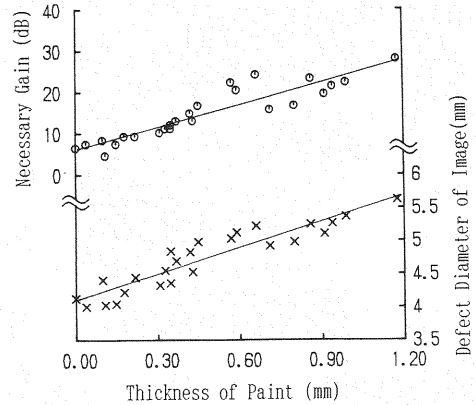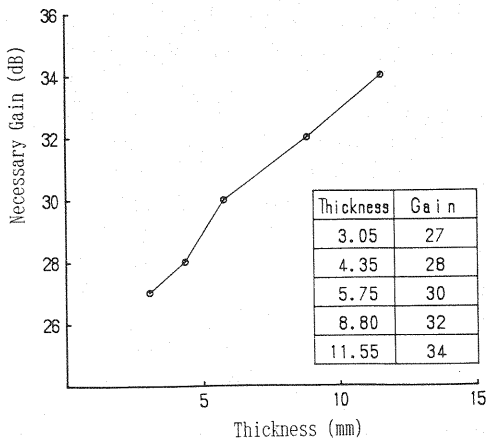

Fig.17   Effect of paint on steel surface

Fig.16   Relation of steel thickness and necessary gain
(For bottom echo)

Thickness	Gain
3.05	27
4.35	28
5.75	30
8.80	32
11.55	34

Thus the necessary gain values chosen to detect by a good defect images depending on the surface roughness exist which are shown by the mark ◯ and scaled by the ordinate of left hand side in **Fig.14**. We can find in **Fig.14** that if the surface roughness becomes large, detected sizes of defect images become scattered by large variance and the defect is detected by larger sizes. And again necessary gain values to be used depending on the condition of surface roughness of the specimen are given in **Fig.14**. The variation range of necessary gain values to be chosen as a function of parameter a of power spectrums of surface roughness are shown in **Fig.15**, and the necessary gain values are given by the range from 20 dB to 40dB. Thus we can find out an appropriate gain value in the field test depending on the surface roughness of the structural member.

(2)   **Effect of thickness of specimen on the image**

Because of the thickness of specimen the attenuation effect on the ultrasonic echo is essential and necessary to have data to choose an appropriate frequency of probe and an amplifying gain value at a measurement. To obtain a relationship between a necessary gain value and a thickness of specimen, five specimens of defferent thickness by 3.05mm, 4.35mm, 5.75mm, 8.80mm and 11.55mm are used in this experiment. Each specimen has a drilled hole of same diameter 4mm and different length. The length of drilled hole is made approximately a half of thickness of specimen and they are 1.53mm, 2.18mm, 2.88mm, 4.40mm and 5.78mm, respectively. The necessary gain values to get a good result of image are increased by a function of thickness of specimen as shown in **Fig.16**.

(3)   **Effect of paint on the specimen**

As a field inspection by C-scan method we have to measure a structural member through the layered paint. If the thickness of paint is thick, because of a damping effect we have to choose a necessary gain to get a accurate image of the defect. The 26 specimens with different thickness of paint and with the drilled holes of same diameter 4mm are used. The defect size of detected images as a function of paint thickness are plotted by the mark × and scaled by the ordinate of right hand side in **Fig.17**. And if the paint thickness becomes thick, the necessary gain value (shown by mark ◯) to get a good image of defect becomes high, and then the defect diameter of detected image becomes larger than the real diameter 4mm as shown in **Fig.17**.

(4)   **Experiment of a modified method for immersion field testing**

In the case by immersion ultrasonic testing we can obtain more accurate image of defect by using higher frequency of probe than a direct scan method. As we, however, have to put the specimen
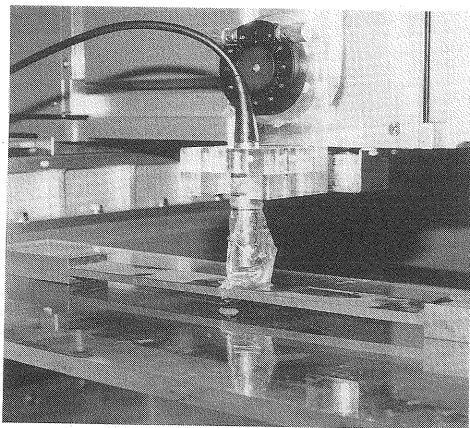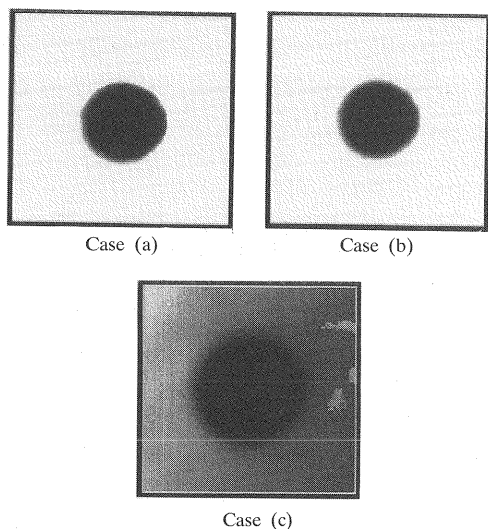
Fig.18   A probe with a water bag in Case(b)

Case (a)   Case (b)

Case (c)

Fig.19   C-scan images by three testing methods (10×10
mm, pitch 0.05 mm, scale ⊢———⊣ 1.6 mm)

in the water tank, it is difficult to apply the same method of C-scan testing for a field inspection. We need to develop another method not to use the water tank at the field inspection. Thus in this study we tried to test and compare two other methods with a usual immersion method. The specimen is a steel plate of 6mm thick and has a drilled hole of diameter 4mm and length 3mm from the bootom surface. Three different testing methods are

   Case(a) : usual immersion test,
   Case(b) : test by a probe with a water bag
           between a probe and specimen(as
           shown in **Fig.18**), and
   Case(c) : test by using a grease layer between a
           probe and specimen

and the detected images obtained by these three methods are compared in **Fig.19**. The other

parameters are same in all cases. It is found from these results that by using the method of Case(b) we can obtain the same defect image as that by Case(a) and by the method of Case(c) the image may become fuzzy and then be obtained by large diameter of detected image.

6.   ACCURATE ANALYSIS OF BOUND- ARY ECHO BY WAVE ANALYSIS

The detected defect image measured by ultrasonic scanning test is given by the data of echo amplitude. The echo amplitude data consist of the maximum amplitude of boundary and bottom echo which are reflected from the boundary of a defect and lower surface of the specimen. If the location of probe and the focal point of the incident wave reaches to the boundary of the defect, the boundary echo reflected from the boundary of the defect is detected together with the bottom echo reflected from the lower surface of the specimen within the time gate set up by the system. However we sometimes cannot obtain a good defect image with sufficient accuracy in these measurement because of the wave scattering at the boundary of the defect. This scattering effect on the wave reflection depends upon the wave length and shape and size of a defect. Therefore we need a detail analysis of the boundary echo to get the accurate information from the wave on the shape and size of the defect in addition to the C-scan image given by the echo amplitude data.

In this chapter we discuss the precise wave analysis of boundary echo obtained within the time gate set up by the system and find out a method to measure the more accurate size of the defect.

(1)   Experimental measurement

The circular drilled holes of diameter 2mm are made in the steel plate of 9mm thick with three different lengths of 5mm, 3mm and 2mm and we call here these specimen as specimen A, B and C, respectively. The focus of the probe is first adjusted at the center of drilled hole. And the probe with 10MHz resonance frequency scans over the square of the area of 5mm × 5mm on the drilled hole to get the C-scan image of the defect. The reflection waves are received along with the line shown in **Fig.6**(a) by the chained line by 50 μm pitch around the boundary of the defect and by 100 μm pitch for the other area. The reflection waves are transformed to the digital data by using the digital storage oscilloscope (DSO) and stored to a floppy disk. The sampling pitch of time is 0.57nsec and the number of data for the one reflection wave is 4096 points.

In **Fig.20**(a), (b) the typical original data received by the ultrasonic scanning test are shown.
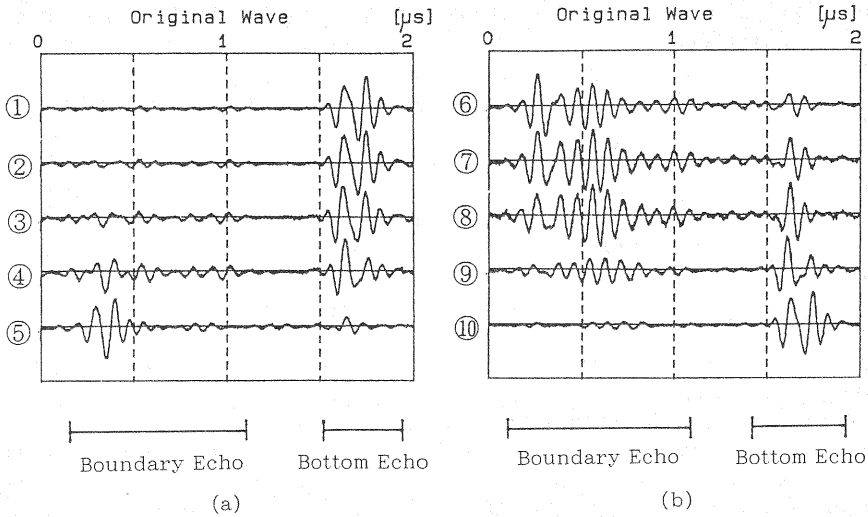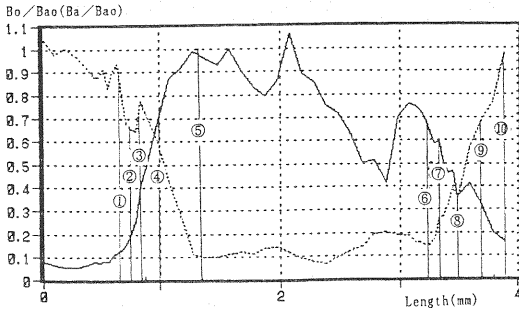
Fig.20 Measured waveforms of specimen A

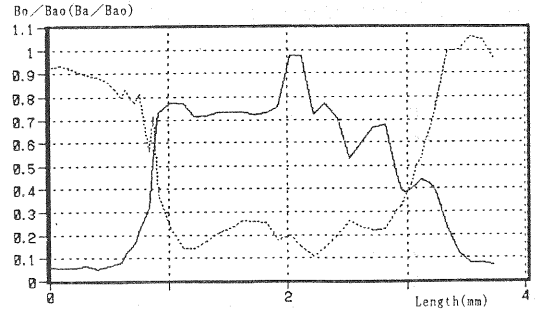Fig.21 Results of (Bo/Bao) and (Ba/Bao) for specimen A

Fig.22 Results of (Bo/Bao) and (Ba/Bao) for specimen B

Fig.23 Results of (Bo/Bao) and (Ba/Bao) for specimen C

In **Fig.20**(a) the transition of the received wave from the bottom echo (wave ①, ②) reflected from the lower surface to the boundary echo (wave ④, ⑤) reflected from the defect, when the center of the probe comes into the defect, is clearly shown. And in **Fig.20**(b) another transition of the received waves from the boundary echo to the bottom echo, when the probe goes out across the defect boundary, is also shown.

In these figures the amplitudes of the waves are normalized by the maximum amplitudes of each waves and the abscissas are scaled by microsecond (μs). The numbers shown in **Fig.20**(a), (b) as ①, ②, etc. indicate the location of the probe where the reflection waves are received and they also correspond to the locations shown in **Fig.21**.

(2) Results obtained by wave analysis

The reflection wave involves both the boundary echo and the bottom echo, and when the probe comes to be close to the defect boundary the amplitude of boundary echo becomes greater than that of bottom echo. Thus there is a boundary of
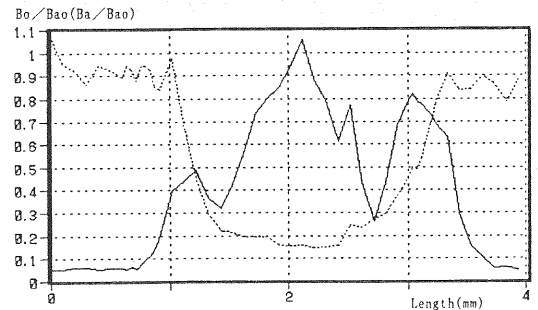
defect somewhere in the transition range. In the defect image analysis by using the maximum amplitude of the reflection wave we receive the greater amplitude of boundary echo within the area of defect as shown in **Fig.20**(a), (b) from the wave number ⑤ to ⑧. As we can separate the boundary echo from the bottom echo in the reflection wave, we can get each maximum amplitude of both the

boundary echo (Bo) and bottom echo (Ba). And the normal maximum amplitude of the bottom echo (Bao) is also obtained far from the defect boundary.

The ratios between the maximum amplitude of the boundary echo (Bo) and the normal maximum amplitude of the bottom echo (Bao) are shown in **Fig.21, Fig.22** and **Fig.23** by the solid lines in the cases of specimen A, B and C, respectively, and the ratios between the maximum amplitude of the bottom echo (Ba) and the normal maximum amplitude of the bottom echo (Bao) are also shown by the dotted lines. The abscissa is scaled by the distance in millimeter (mm).

We can see in three figures that the ratios of Ba/Bao become small within the length nearly equal to 2mm which correspond to the size of real defect. And the distribution of the ratios of Bo/Bao means the undulations of the drilled hole tips because they correspond to the distribution of maximum amplitude of boundary echo. And by the comparison among three results of Bo/Bao we can find that if the depth of the defect becomes deeper the Bo/Bao values become smaller at the boundary of the defect.

7. CONCLUSION

Summarizing the above study on the precise analysis of the reflection wave received by the ultrasonic scanning test to get a improved images of the defect, we have come to the conclusions as follows ;

(1) Twelve C-scan images of defects are obtained by using ultrasonic scanning system together with the path length data which is used to make the defect boundary of image clear.

(2) 3D images of defect shapes are obtained by a CG software on a workstation using both the maximum amplitude data and path length data. We call here this 3D image as a D scope image.

(3) In order to apply this C-scan measurement of ultrasonic scanning test to the field inspection, the effects of surface roughness and thickness of the specimen on the C-scan image of defect are obtained.

(4) To apply the immersion ultrasonic test to the field inspection we studied the method to use a small water bag between a probe and a specimen and could get the same C-scan image as one given by a usual immersion test.

(5) By a precise waveform analysis of the reflection wave we can obtainthe more accurate defect size given by the distribution of the ratios between the boundary and bottom echo and the normal bottom echo without any scattering effect from the defect.

REFERENCES

1) Thompson, D.O. and Chimenti, D.E. : Review of progress in quantitative nondestructive evaluation, Plenum Press, Vol.1 (1981)~Vol.10 (1991).

2) Miki, C., Fukazawa, M., Katoh, M. and Ohune, H. : Feasibility study on crack detection of fillet welded joint, Proc. of JSCE, No.386, pp.329~337, 1987.(in Japanese)

3) Iijima, T., Hukami, M., Miki, C. and Tajima, J. : Study on fatigue crack detection in stiffening truss chord members, Proc. of JSCE, No.410, I-12, pp.445 ~ 454, 1989.(in Japanese)

4) Krautkrämer, J. and Krautkrämer, H. : Ultrasonic Testing of Materials, Springer-Verlag, 1977.

5) Hull, B. and John, V. : Non-Destructive Testing, Macmillan Education, 1988.

6) Mikami, S., Yamazaki, T., Sugawara, N. and Oshima, T. : Study on the improvement of small defect detection for steel structure by means of ultrasonic pulse echo method, Proc. of The Symposium on Non-Destructive Evaluation in Civil Engineering, JSCE, 1991. (in Japanese)

7) Sugawara, N., Yamazaki, T., Terada, H. and Oshima, T. : Study on the accuracy of defect detection for the images by ultrasonic testing, Proc. of The Hokkaido Branch of JSCE, 1992. (in Japanese)

8) Precision Visuals, Inc. : PV-Wave Overview, 1988.

(Received May 29, 1992)