Development of Air-Coupled Ultrasonic Inspection Device for Spacecraft Insulation

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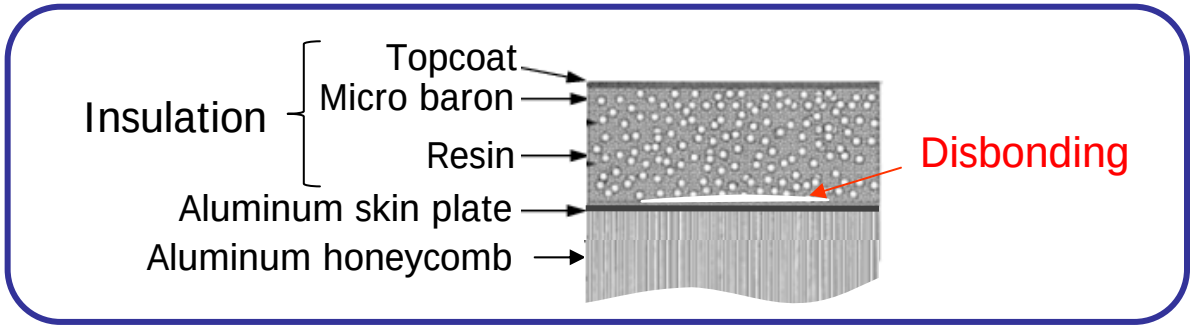
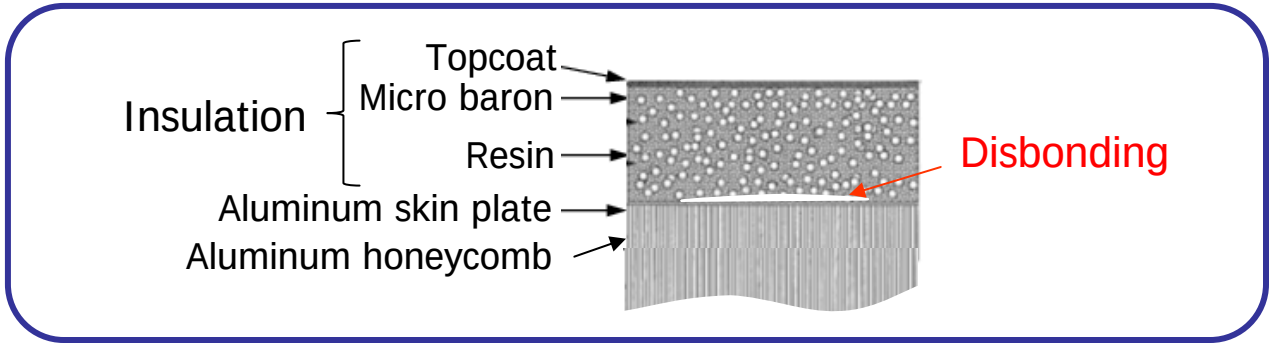
Purpose of this study

- **Purpose**
  - Detection of disbonding at payload fairing of rocket
- Investigation of location and feature of disbonding
  - Disbonding at the interface between insulation and skin plate of aluminum honeycomb is concerned.

H-IIA Launch Vehicle
(Courtesy of JAXA)

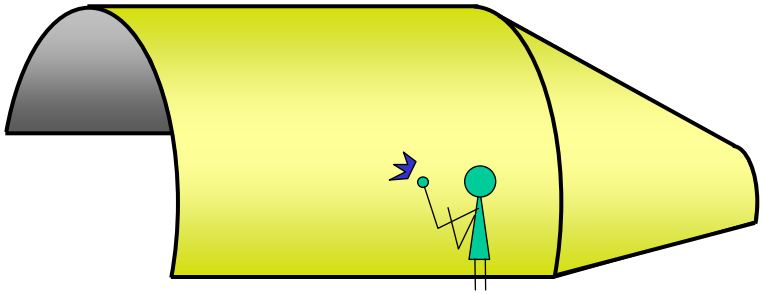


BACKGROUND



NDT Methods for Insulation

- Conventional NDT Methods
  - Tap test

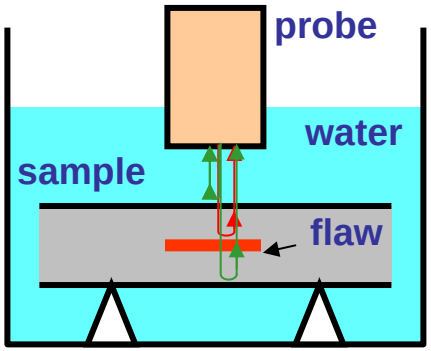


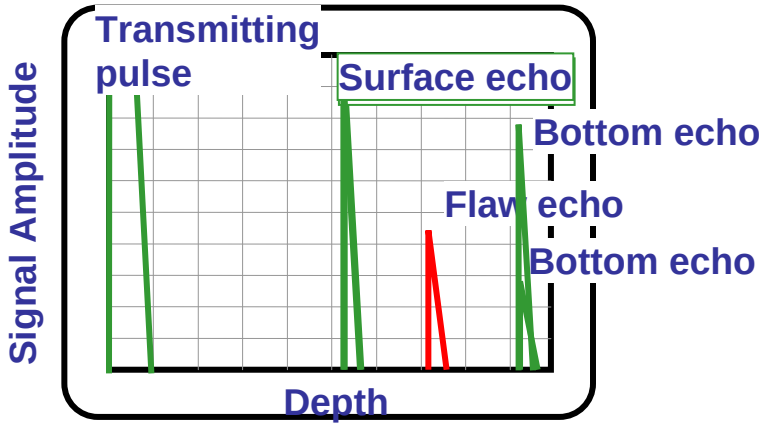
- Problems
  - Record ability
  - Objectivity
  - Dependence on NDT personnel
  - Efficiency

BACKGROUND

- Ultrasonic Testing
  - Immersion technique
    - Stable coupling

- Problems
  - Liquid couplant
    (Testing objects are drenched.)
  - Large-scale system is necessary for large component.

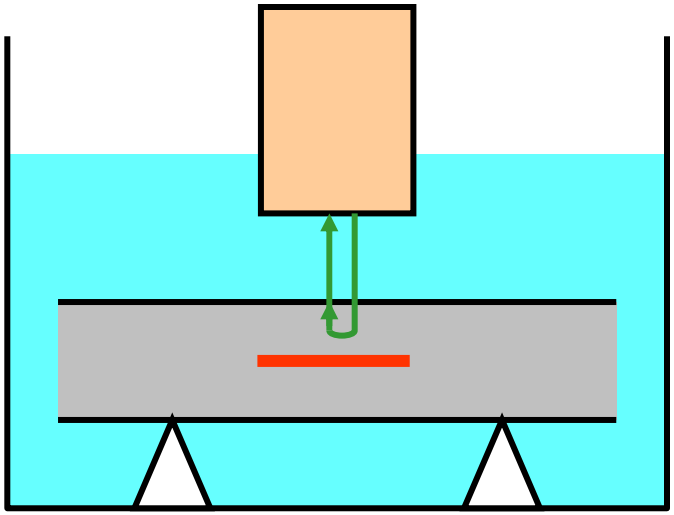




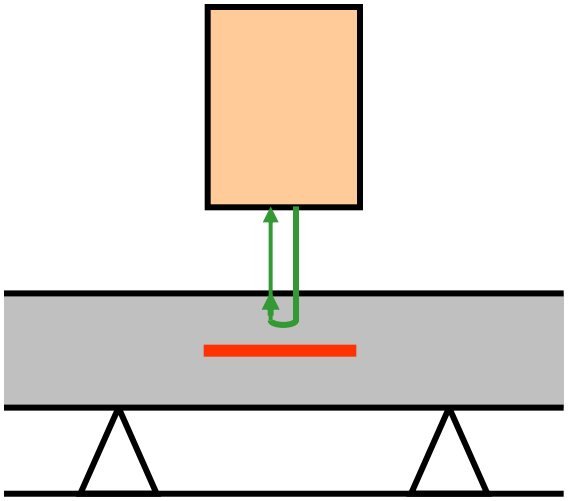
Schematic diagram of Ultrasonic testing (Immersion technique)

Problems of *Conventional UT*

- One of the major problems is that liquid couplant is required during inspection.
- Non-contact (No-couplant) technique is required.



Immersion technique

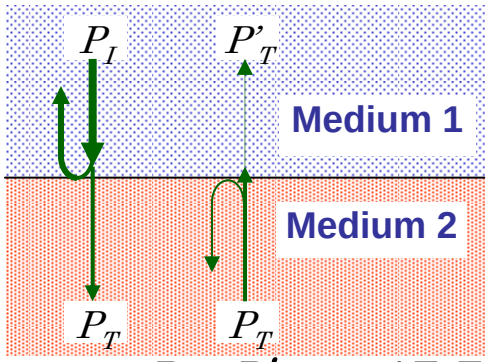


Air coupled technique

Air-coupled ultrasonic inspection technique is expected to solve the problem.

Problems of *Air-Coupling*

- Attenuation of ultrasound is much more remarkable in the air than that in water.
- Reflection coefficient between air and test material is very large.



$$T_{1\to 2} = \frac{P_T}{P_I} \cdot \frac{P'_T}{P_T} = \frac{4Z_1Z_2}{(Z_1+Z_2)^2}$$

Z : Acoustic impedance

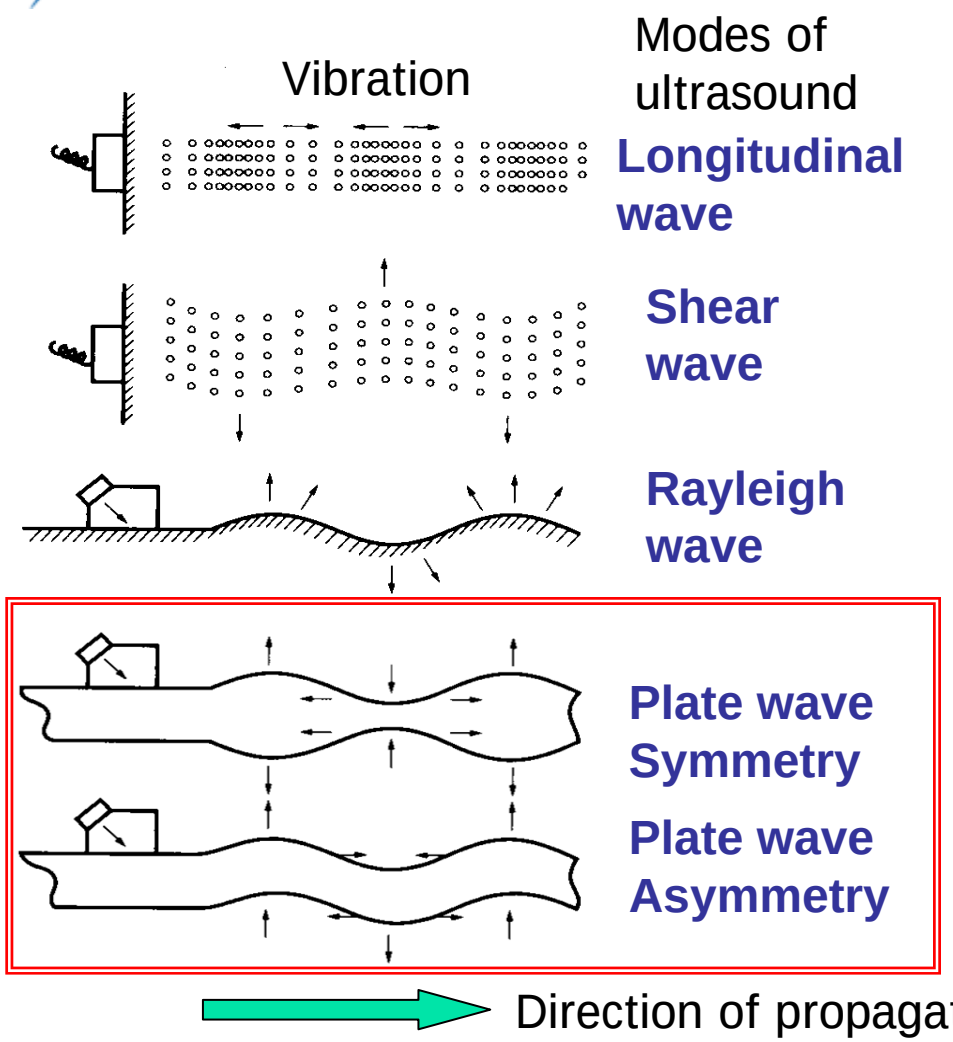
$Z = \rho$ (Density) X C (Sound Velocity)

- Echo transmittance : $T_{1\to 2}$

Medium 2 \ Medium 1	Water (Z_{water}=1.48)	Air (Z_{air}=4×10^{-4})
Acrylic resin (Z_{acryl}=3.22)	0.86	5.6×10^{-4}
Aluminum ($Z_{aluminum}$=16.9)	0.84	9.5×10^{-5}

Echo transmittance ratio into the air is about 1/10000 comparing that into water

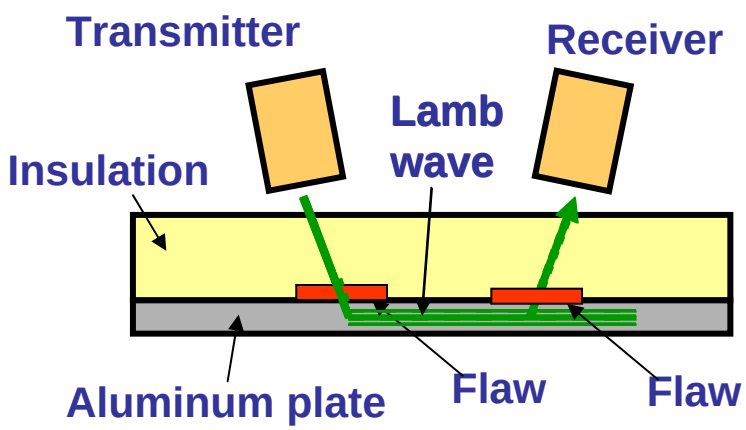
Solutions of the Problems
Selection of wave mode



- There are some modes of ultrasonic wave in solid material.
- Plate wave (Lamb wave) propagate along the thin material, and each mode of plate wave is generated by a specific incident angle dependent on frequency and thickness of material.

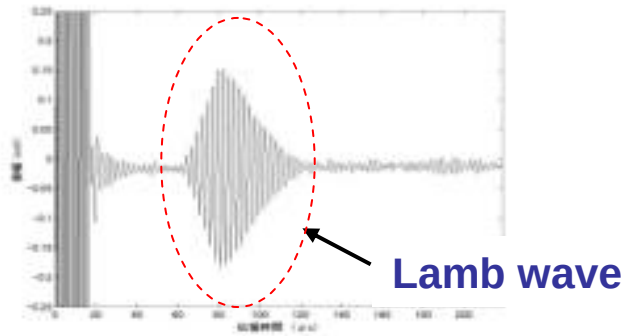
Solutions of the Problems
Using Lamb Wave

- Principal
  - Flaws under transmitter or receiver can be detected.

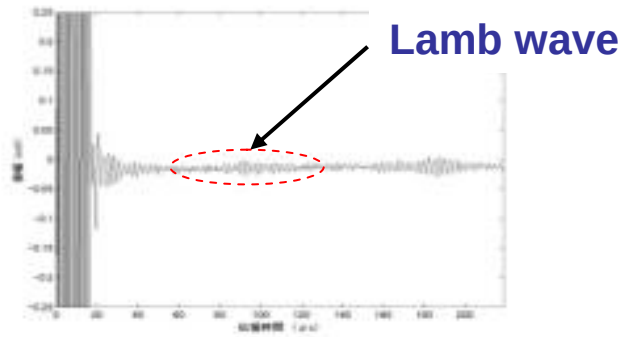


In this paper, here-in-after, air-coupled ultrasonic inspection technique is abbreviated as ***ACU***.

- Testing results
  - Signal at the sound part



  - Signal at the flaw part



Decrease in amplitude of Lamb wave

Determination of Test Condition

- **Key issues**
  - High attenuation of ultrasound in the air
  - Lamb wave is generated by specific incident angle

- **Requirements**
  - Construction of system considering
    - the characteristics of probe and instrument,
    - selection of frequency, etc

Selection of Optimum Condition

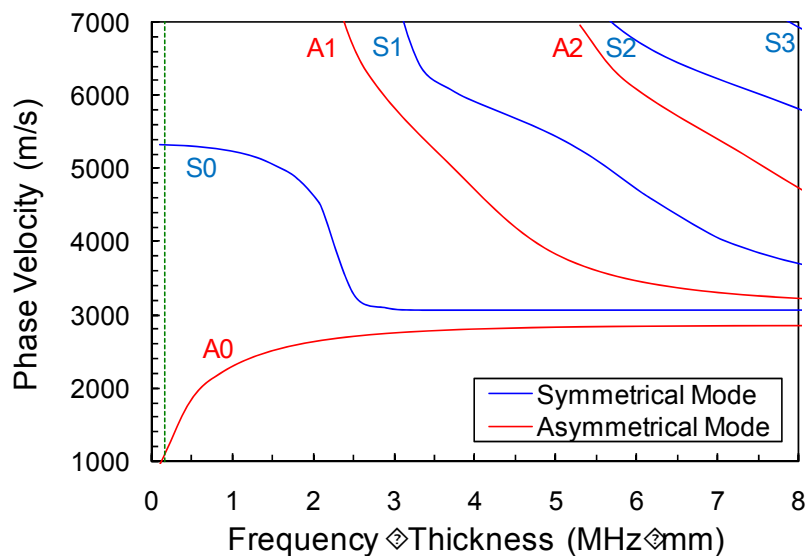
Symmetry mode $$4pq\tan\frac{\pi fd}{c}q+\left(p^2-1\right)^2\tan\frac{\pi fd}{c}p=0$$

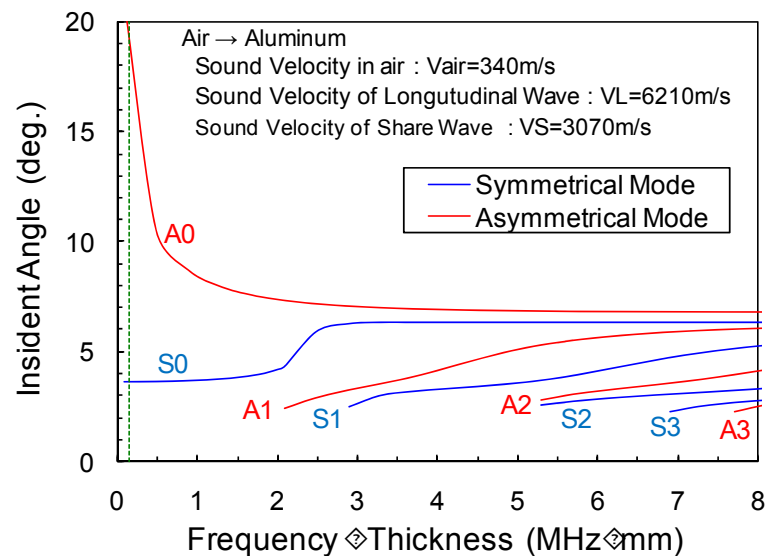
Asymmetry mode $$\left(p^2-1\right)^2\tan\frac{\pi fd}{c}q+4pq\tan\frac{\pi fd}{c}p=0$$

$$p^2=\left(\frac{c}{c_S}\right)^2-1 \qquad q^2=\left(\frac{c}{c_D}\right)^2-1$$

c : Phase velocity
f : Frequency
d : Thickness of material,
C_D : Sound velocity of longitudinal wave
C_S : Sound velocity of shear wave

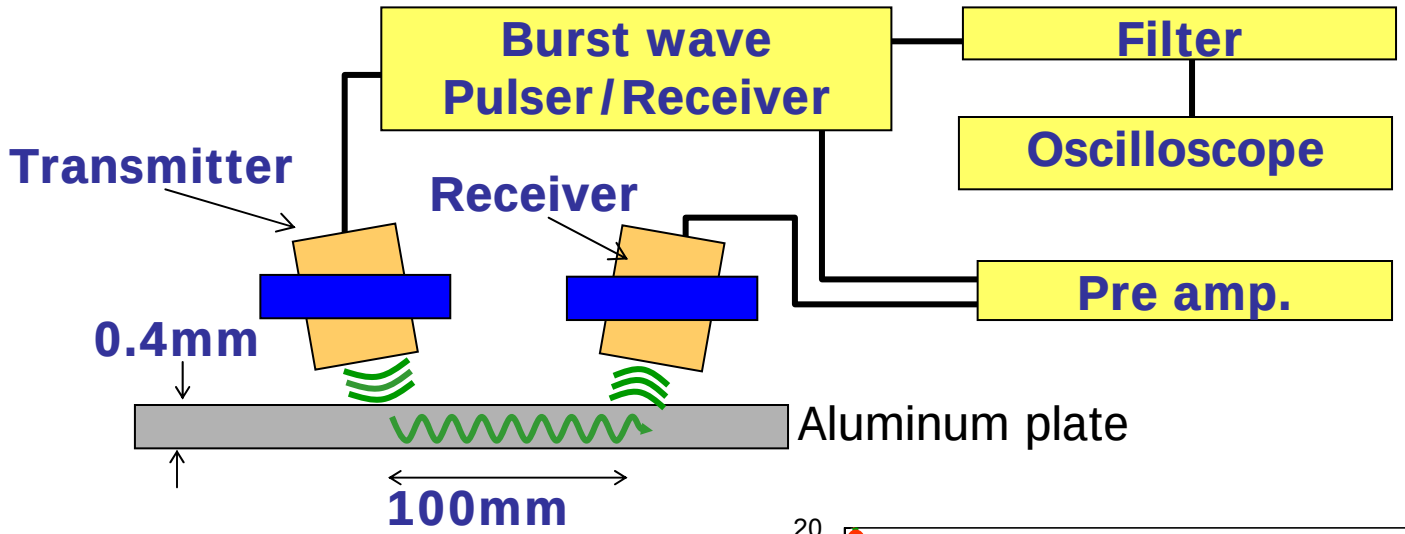
Air : C_L=340(m/s) → Aluminum : C_D=6,210(m/s), C_S=3,070 (m/s)



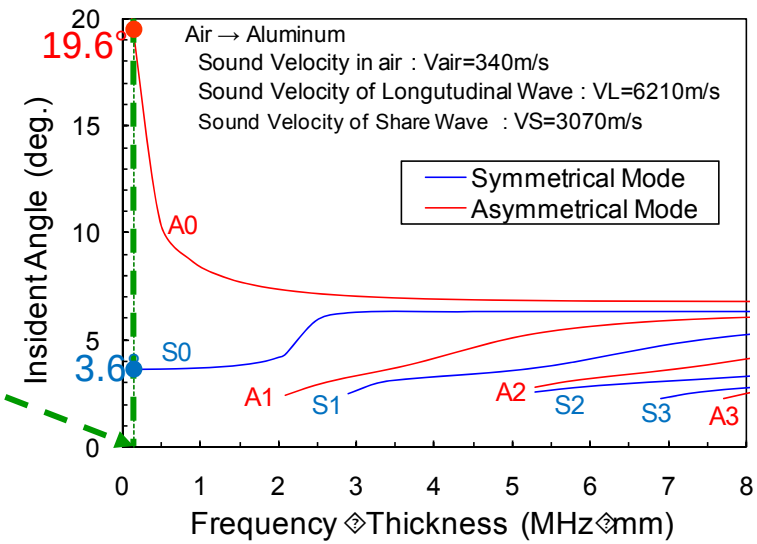


Calculation results of phase velocity of Lamb wave in aluminum plate

Generation of Lamb Wave



Material : aluminum
Thickness : 0.4mm
Exciting frequency : 380kHz
Exciting wave number : 15



Characteristics of Lamb Wave

- **Comparison between the theoretical result and the experimental result**

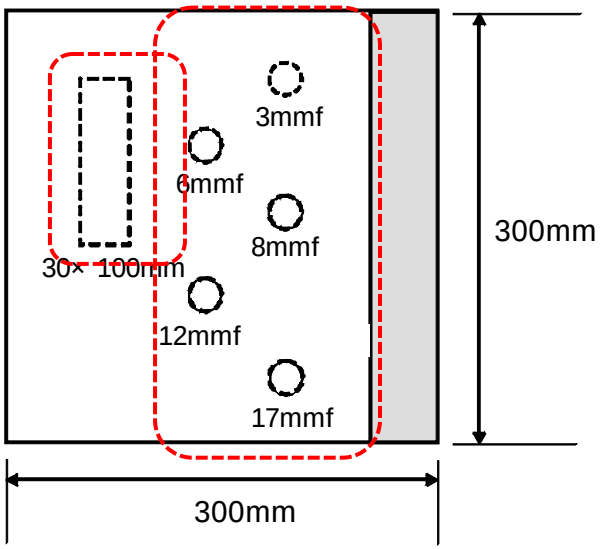
Mode of Lamb Wave	Experimental results		Theoretical solution	
	Incident Angle	Phase Velocity	Incident Angle	Phase Velocity
S0	Not Received	Not Received	3.6 °	5330m/s
A0	18 °	1190m/s	19.6 °	1070m/s

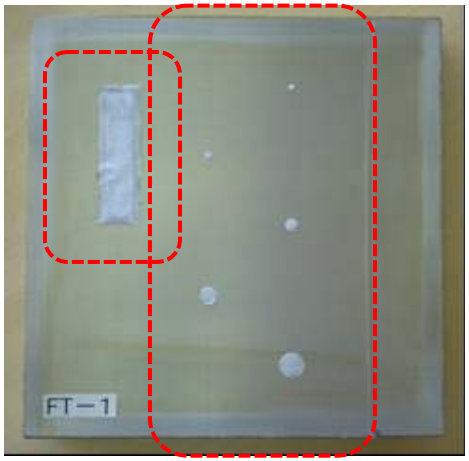
(1) Lamb wave of A0 mode predicted by the theoretical solution could be received experimentally.
(2) The Lamb wave of A0 mode could be received clearly, since the attenuation of the A0 mode was lower than that of the other modes.
(3) Lamb wave of S0 mode could not be received experimentally.

Lamb wave of A0 mode was used in the following experiments.

Detection of Artificial Flaw (Disbonding) of Test Specimen

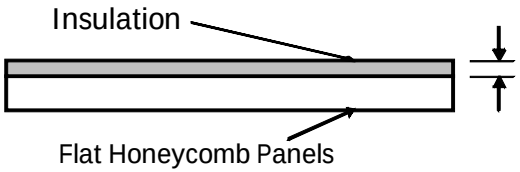
- Type A : Detectability of disbonding,
  Frequency dependance





Before pasting insulation

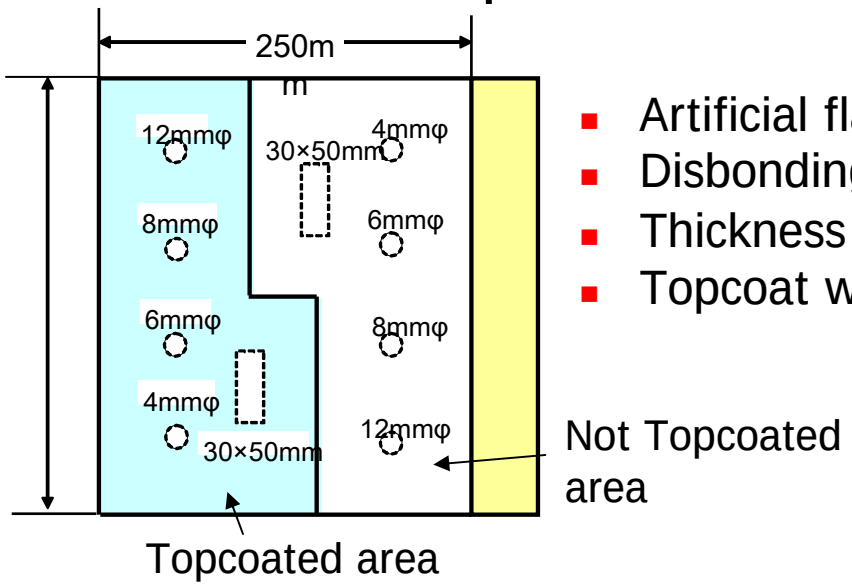
After pasting insulation



- Artificial flaw: four sheets of Tefron of 0.05mm^t
- Disbonding Size : 3, 6, 8, 12, 17mmφ, 30×100mm
- Thickness of Insulation :2, 4, 6mm

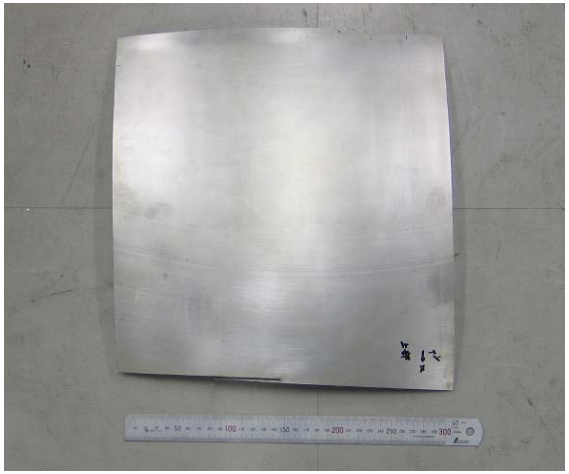
Detection of Artificial Flaw (Disbonding) of Test Specimen

- Type B: Thickness of insulation and Topcoat dependence
  Comparison with Tap test



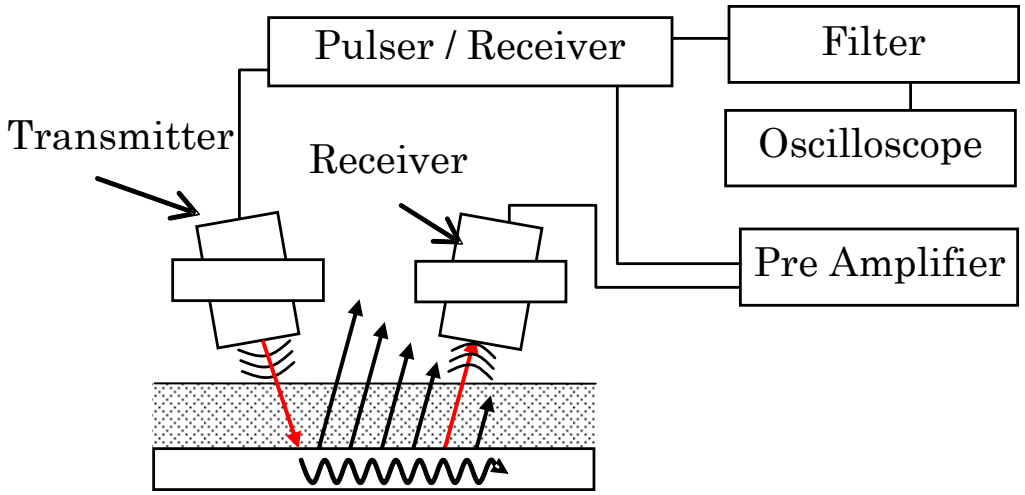
- Artificial flaw: four sheets of Tefron of 0.2mm^t
- Disbonding Size : 4, 6, 8, 12mmφ, 30×50mm
- Thickness of Insulation :2, 4, 7.5mm
- Topcoat was pasted up on the half area of insulation

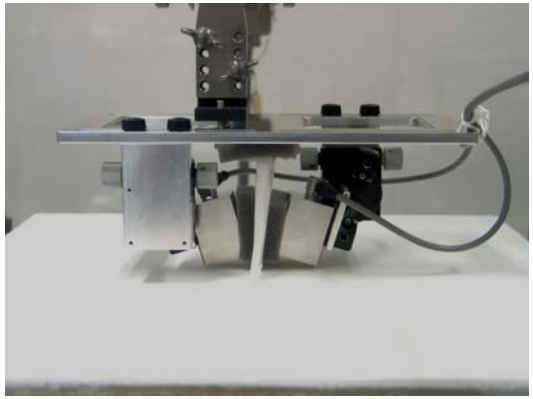
- Type C: Effect of curvature
  - Artificial flaw: not inserted
  - Curved aluminum plate : 4.8mm^t



Detection of Artificial Flaw (Disbonding) of Test Specimen

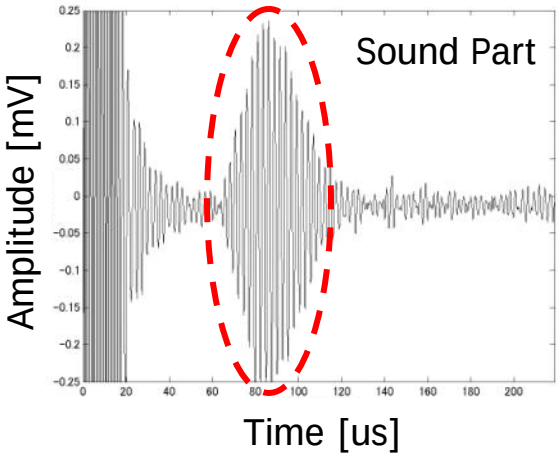
- Experimental Equipment
  - Probe
    - Nominal Frequency : 200kHz,400kHz or 600kHz
    - Element Size : 14×20mm
  - Experimental System

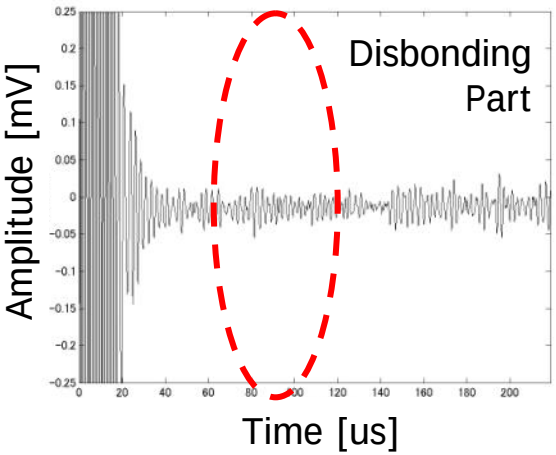




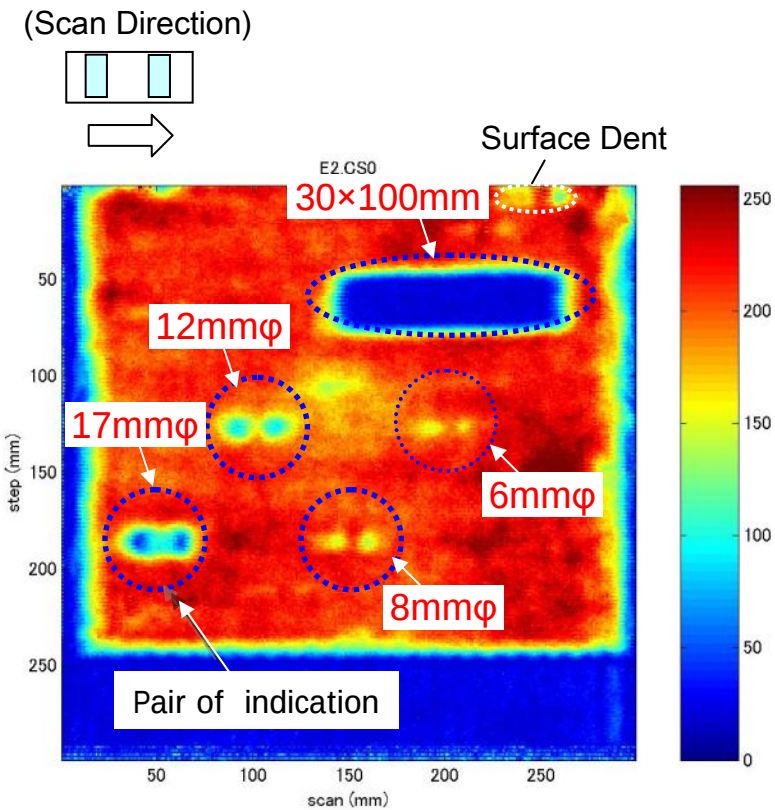
Experimental Result 1

Detetability of Disbonding





Thickness of Insulation : 4mm

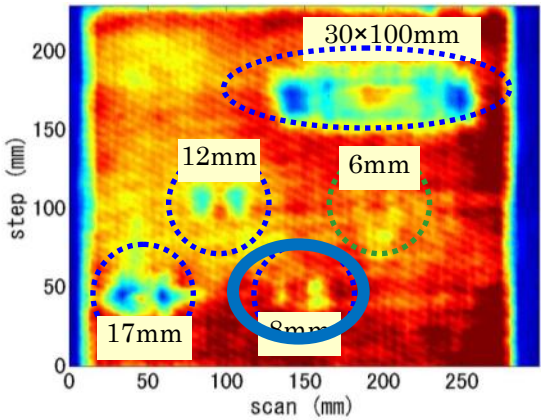


Disbonding of larger than 8mm in diameter can be detected clearly

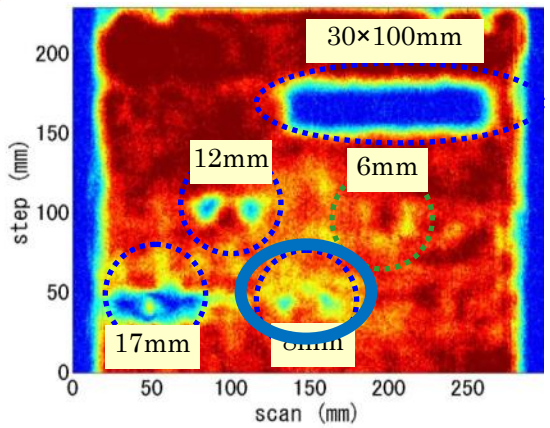
Experimental Result 2

Dependence on nominal frequency

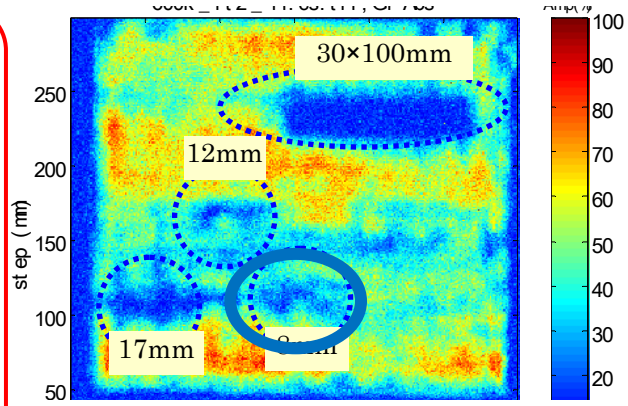
Thickness of Insulation : 4mm



200kHz



400kHz



600kHz

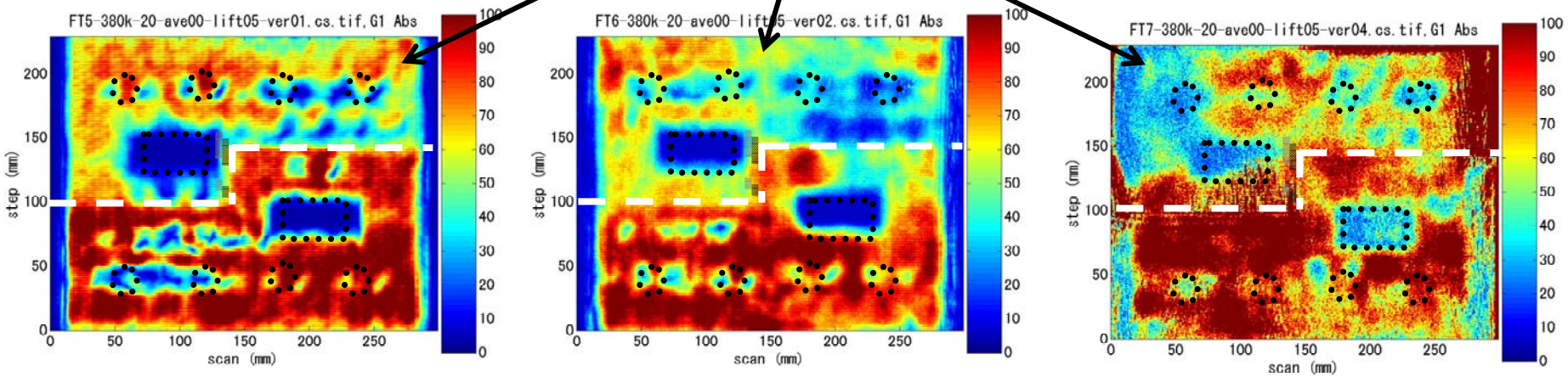
Probes with the nominal frequency of 400kHz is most efficacious.
Indication of disbonding with a diameter of 8mm can be obtained clearly.

Experimental Result 2

Topcoat effect

Nominal frequency of probe: 400kHz

Topcoated area



2mm 4mm 7.5mm

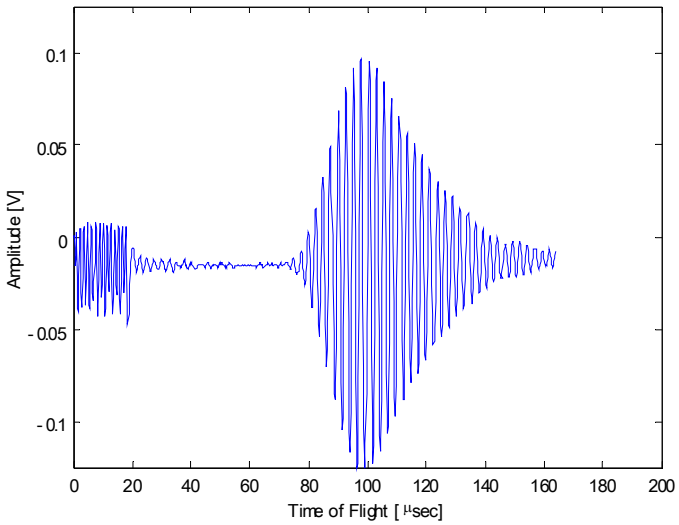
Thickness of insulation

the disbonding with a diameter of 8mm could be detected regardless of the thickness of insulation.

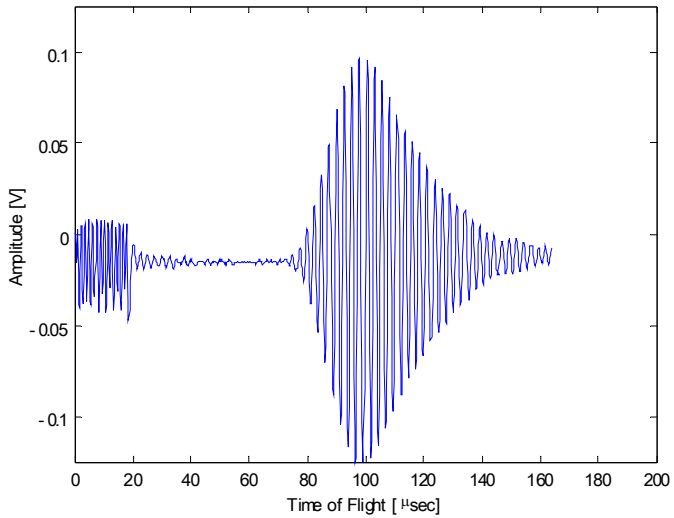
Detectability of disbonding is not depend on the topcoat.

Experimental Result 3

Effect on curvature of object



Curvature



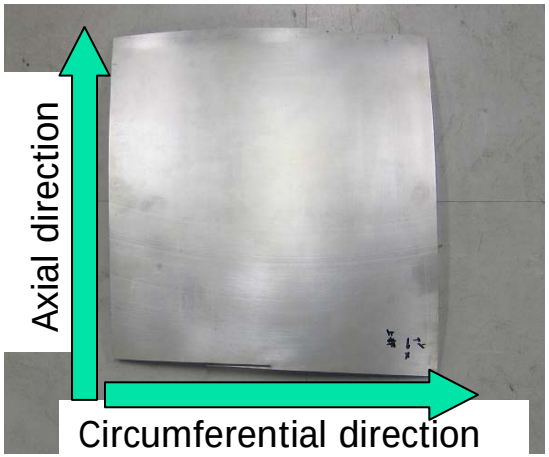
Flat

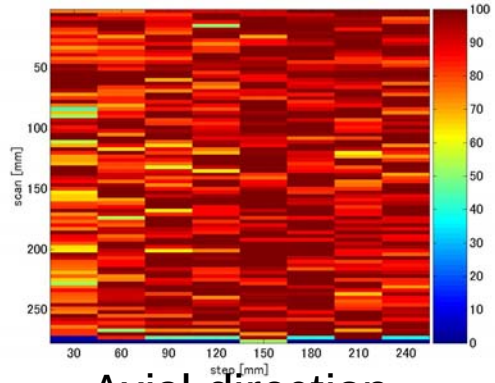
Ratio of Amplitude (Curvature/Flat) : 0.96

Significant difference of signal amplitude can not be observed.

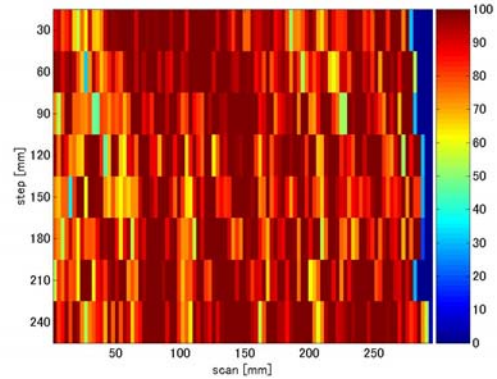
Experimental Result 3

Effect on curvature of object

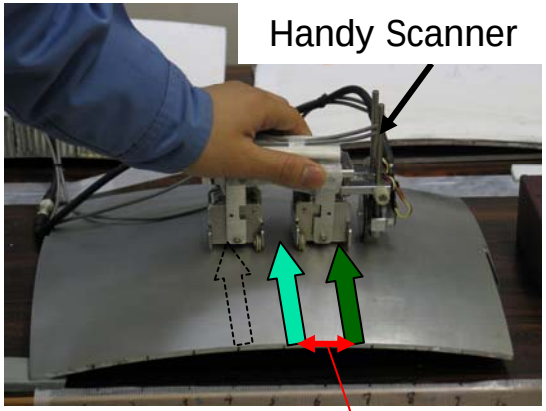




Axial direction



Circumference direction



Scanning pitch : 30mm

The amplitudes were almost the same.
(There were some changes in amplitude.)

This technique could be applied not only to flat specimen, but also to curved specimen.
A mechanism is required to keep the incident angle of ultrasound to the surface of specimen.

Experimental Result 4

Comparison with Tap Test

- without Topcoat

Thickness of Insulation		2mm	4mm	7.5mm
Air-Coupled Ultrasonic Test	200kHz	φ4mm	φ8mm	φ8mm
	400kHz		φ4mm	
	600kHz			Low S/N
Tap Test		φ8mm	φ8mm	30×50mm

- with Topcoat

Thickness of Insulation		2mm	4mm	7.5mm
Air-Coupled Ultrasonic Test	200kHz	φ4mm	φ6mm	φ12mm
	400kHz		φ4mm	φ8mm
	600kHz		30×50mm	Low S/N
Tap Test		φ8mm	φ4mm	φ8mm

Detectability of ***ACU*** is the same or superior to that of Tap test.

CONCLUSION

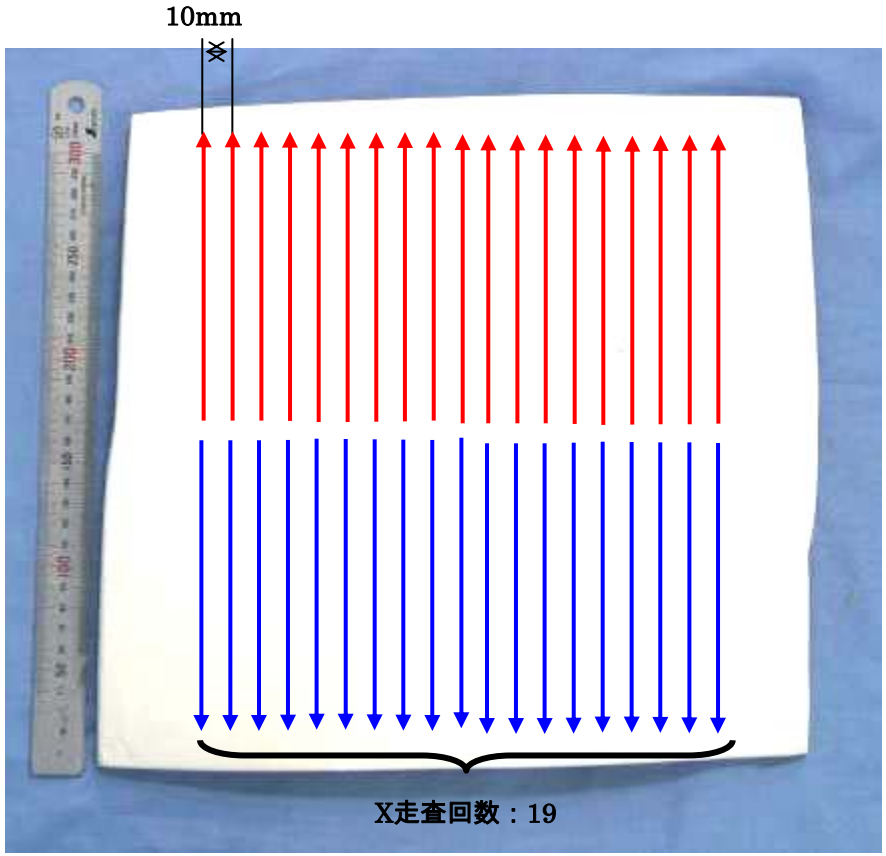
- Air-coupled ultrasonic inspection technique using Lamb wave was investigated.
  - Applicable to detect dinbonding with a diameter of larger than 8mm.
    - Detectability of ACU is the same or superior to that of Tap test.
  - The detectability does not depend on:
    - thickness of insulation by selecting optimum probe.
    - curvature of testing object.
    - top coat

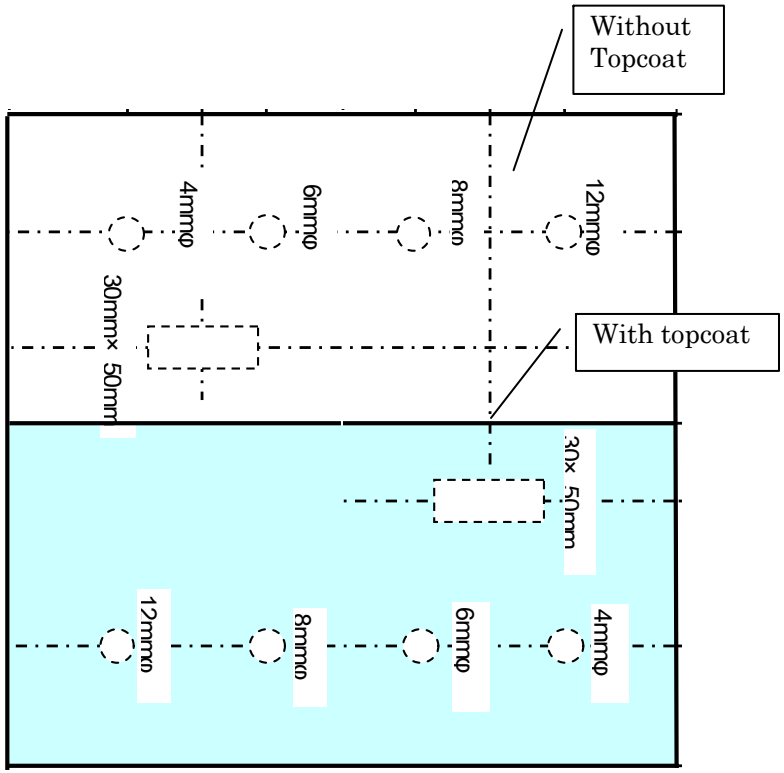
- This technique :
  - Can be expected to detect disbonding easily.
  - Will be applied to field inspection in the near future.

To be continued

Thank you for your attention !

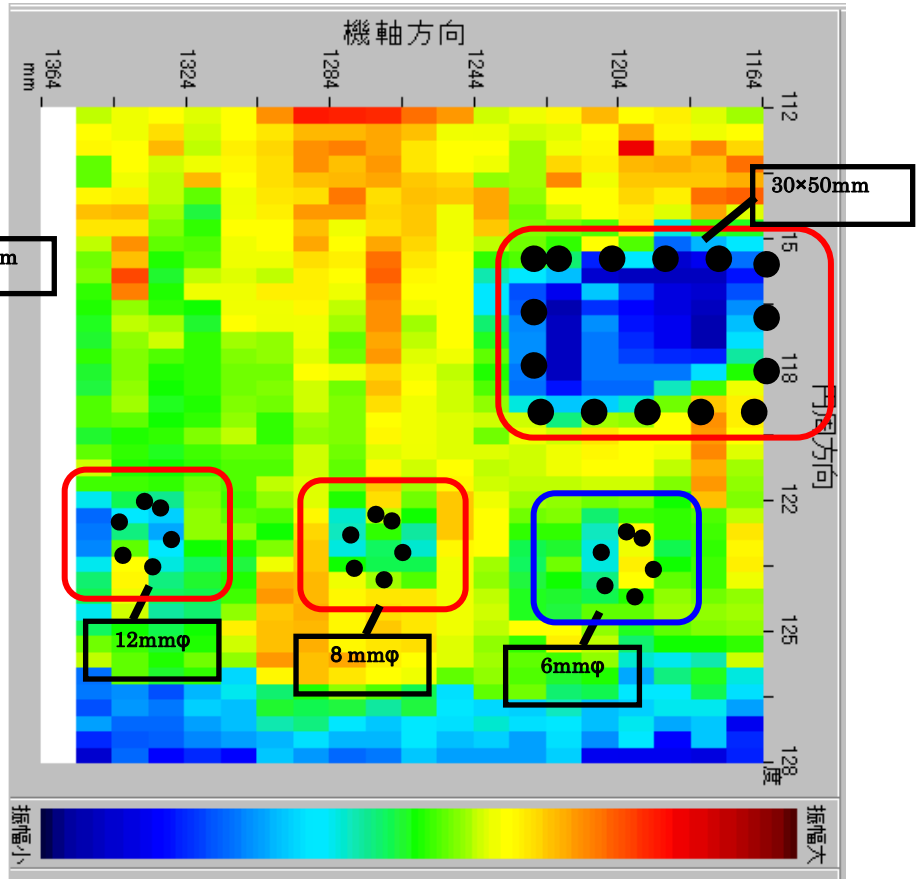
Verification



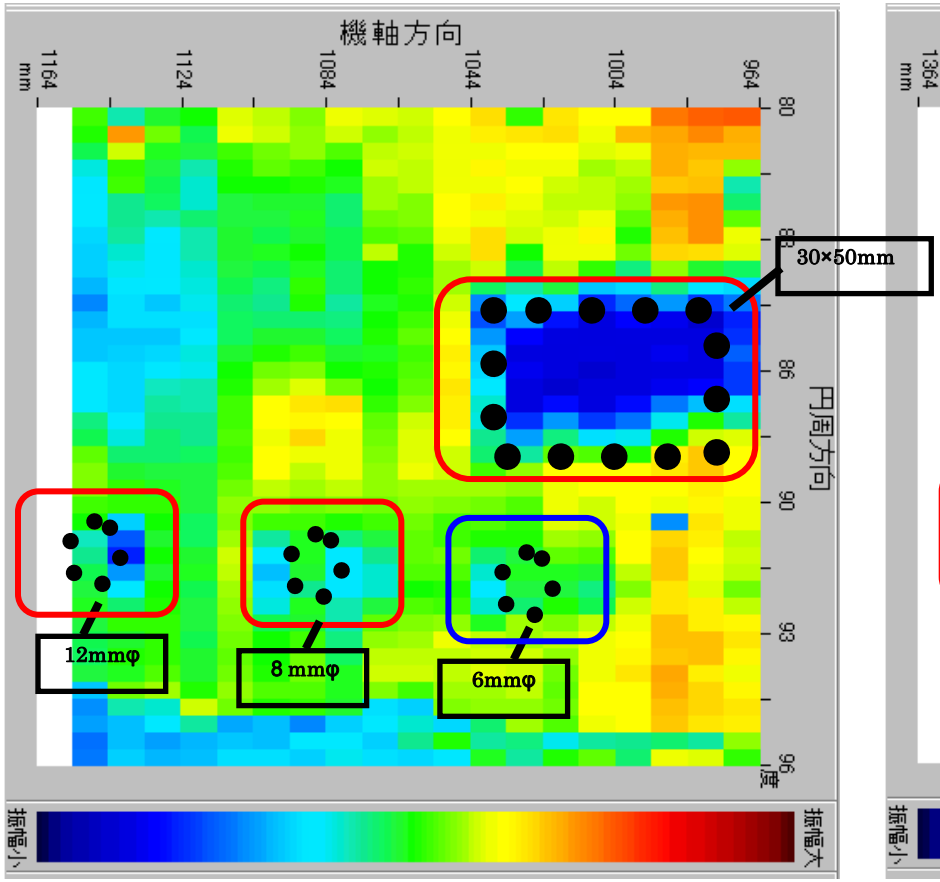


Verification

Verification



without Topcoat



with Topcoat