

## Study Committee D1

### Materials and Emerging Test Techniques

#### Paper D1-PS1-10646

## Nondestructive Terahertz and Millimeter Wave Imaging for Underfilm Corrosion

N. Fuse<sup>1</sup>, Y. Hori<sup>1</sup>, T. Takahashi<sup>2</sup> and M. Mizuno<sup>2</sup>

<sup>1</sup>Central Research Institute of Electric Power Industry, <sup>2</sup>National Institute of Information and Communications Technology

### Target: Corrosion in coated steels

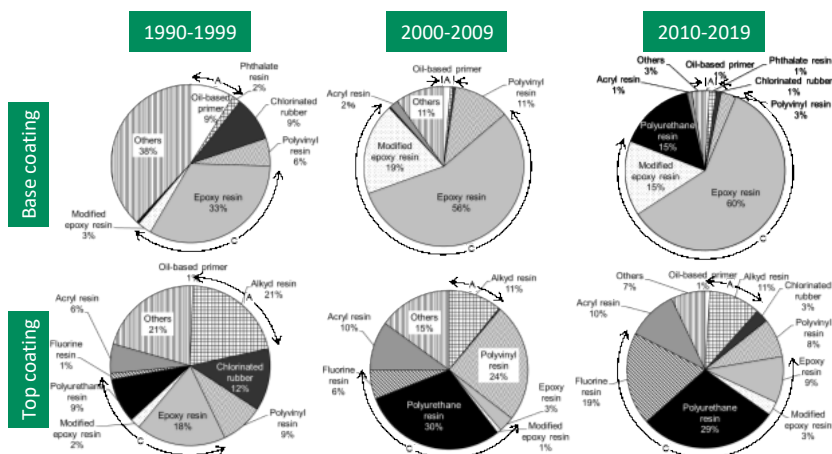
**Corrosion of coated steels** is one of the main concerns for aged outdoor installations. Substrate damage and repair costs will be reduced if **corrosion under opaque coatings can be visualized**. Table 1 summarizes several diagnostic techniques used for the detection of rust and defects. **Traditional methods rely on the experience and subjective opinion of inspectors**. Thus, alternative methods are required to ensure objectivity and continuity of inspections even in the light of workforce reductions.

	Inspection objectives	Methods	Sensing capability		Locating abnormality	On-site application	Chemical analysis
			Surface	Interior			
Anti-Corrosion films	Alligating, peeling, discoloration	Visual inspection/digital camera	B	D	B	A	C
		Cross-cut test	B	–	C	B	D
		Adhesion test	B	–	C	B	D
	Degradation, water absorption, blistering	Infrared spectroscopy	A	D	B	D	A
		Electrochemical impedance	A	C	C	B	D
		Scanning vibrating electrode	B	C	B	D	D
Steel	Rusting	X-ray fluorescence	B	C	B	B	A
	Cracks, defects	Ultrasonic waves	B	B	B	A	D

A: suitable, B: somewhat suitable, C: somewhat unsuitable, D: unsuitable.

### Survey: Coating materials used for transmission lines

**Repair paints** used in public facilities are customized according to their specific requirements and are different for each industry. **A survey was conducted for 41,869 paint cases Japanese power transmission towers recorded since 1976. Two-layer coating is typically used** to realize excellent antiweatherability and adhesion to steel. The coating technology has gradually been shifting from oil-based primer/alkyd resin systems to epoxy/polyurethane resin systems that comprise 30% of recent records. **Such paints were found to comply with general "A" and "C" systems.**



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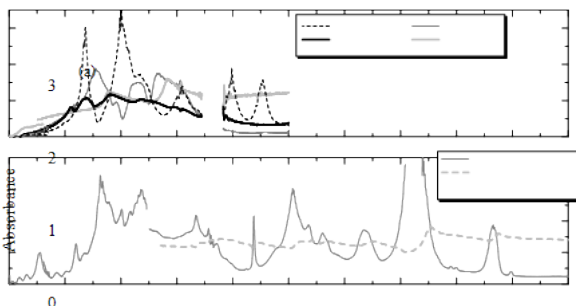
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## Approach from spectral insight

**Absorption spectra in far infrared region:** Steel rusts have characteristic spectral features that depend on their chemical structure. The absorption of an epoxy coating becomes low at frequencies lower than approximately  $300\text{ cm}^{-1}$ .

**Electromagnetic waves in far infrared region, such as terahertz waves and millimeter waves exhibit good transparency for the coatings for effective detection of hidden rust.**

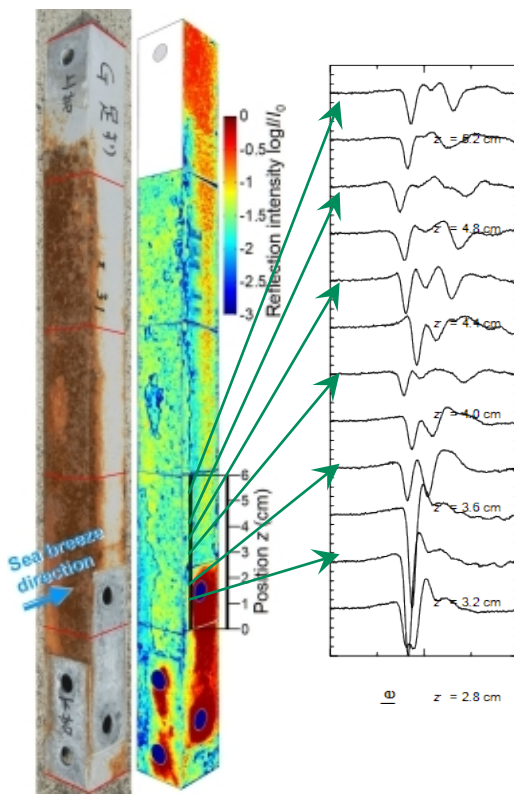


## Imaging by terahertz (THz) waves

**Time-of-flight measurements of THz pulse waves** are typically realized using photoconductive antennas, whereas lock-in technologies with delay lines are used for signal observation. **Two-dimensional catoptric scanner** can detect locations where **THz wave reflections are attenuated by rusting under the coating**.

**A bar sample was removed from a power transmission tower** in a coastal area for inspection. The external appearance indicated that the corrosion was the most intense on the surface facing the sea breeze, as most of the epoxy coating was lost. The reflection intensity of the THz waves was weak on this surface. This indicated the presence of underfilm corrosion.

Reflected THz waveforms (right): **The layered structure of the metal, rust, and coating induced a series of echoes** at their interfaces when irradiated with THz pulse waves. Among the three reflection peaks observed for the areas where the coating remained intact, the second and third correspond to the reflection at the coating/rust and rust/steel layer interfaces, respectively. **The rust thickness was determined from their time delay to be 110  $\mu\text{m}$ , which agreed with direct measurement.**



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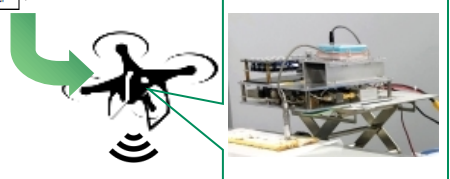
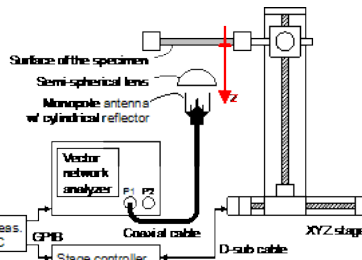
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**Imaging by millimeter waves (MMWs)**

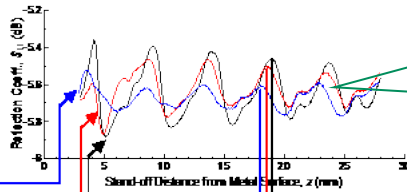
Severe corrosion cannot always be revealed by THz waves. The focus is therefore shifted to **MMWs, which have negligible scattering and also demonstrate good transmissivity.**

MMW antennas are already being mounted on drones for collision avoidance. **Fast imaging is, therefore, expected to be realized by arraying such small devices.** Because the diffusion of MMWs needs to be controlled for inspections, **a semispherical lens was adopted** herein to assess their effect. **Authors also developed a portable and affordable phase shift modulation module.**



**Imaging results**

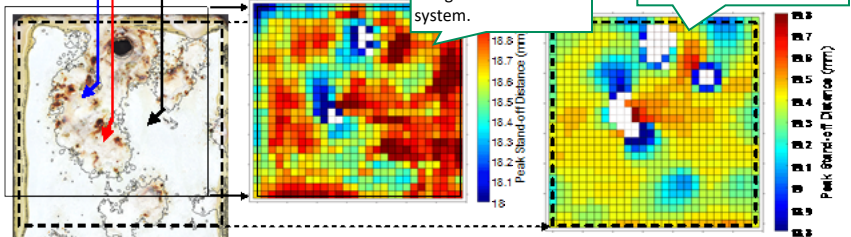
- A rolled steel meeting JIS standard, galvanized and coated with siliconized epoxy resin ( $t \sim 40 \mu\text{m}$ ).
- A cyclic corrosion test in line with JASO M 609 was conducted for 1000 cycles, which corresponds to 8.3 years of exposure in Okinawa, Japan



Typical  $S_{11}$  waveforms observed for the sample surfaces. The peak showed delays when the waveforms were obtained for blistered area.

MMW image obtained by traditional open-ended rectangular waveguide (Penn Eng., 1430-1BM1).

MMW image obtained using the lens-antenna system.



The blistered area detected by a 3D microscope was indicated by overwriting the contours.

- The  $S_{11}$  waveforms were observed along the stand-off distance  $z$ . **The waveform showed shift indicating phase delay** when the measurement was conducted on a blistered point.
- **The lens system is confirmed to suppress diffusion up to several cm of stand-off distance to provide clear image.** The image becomes imprecise when traditional waveguide was used.
- **Portable module was also developed using phase shift modulation.** Although not shown due to space limit, the interference intensity became weak when the underfilm corrosion existed, to reproduce the underfilm corrosion area.