Full-Field Inspection Using Pulsed Laser for Nuclear Plants
-Demonstrated by Ultrasonic Simulation Using Finite Difference Method-

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Many of Japan’s social infrastructure facilities are now entering the latter half of their lifetime. In such circumstances, time- and cost-effective in-situ inspection for SCC (Surface Corrosion Cracking) is required urgently even in the power generation plant market. Optical full-field inspection using pulsed electric speckle pattern interferometry (ESPI) realizes time-effective flaw-screening inspection and will be suitable for RBM (Risk Based Maintenance). Full-field inspection using pulsed ESPI was experimentally demonstrated and simulation results using finite difference method determined attractive performance points.

Key Words: Electric Speckle Pattern Interferometry (ESPI), NDI (Nondestructive Inspection), Nuclear Plant, Risk Based Maintenance (RBM), Finite Difference Method

1. Introduction
Currently many social infrastructure facilities are much aged and often require residual lifetime assessment to continue operation. To define accurately the residual lifetime of a plant, accurate in-situ assessment of aging is required. For example about half of nuclear power stations are more than thirty years old and urgent plant maintenance procedures are ongoing. For such circumstances, cost- and time-effective in-situ inspection techniques for the assessment of residual lifetime have been developed. The author previously proposed two stage hybrid inspection using laser methods developing full-field inspection by pulsed ESPI (electric speckle pattern interferometry) and taking it to a basic demonstration test.1) Further experimental results together with computational simulation used to confirm validity of the techniques are presented in this paper.

2. Full-field Inspection Based on RBM

2.1 Attractive Points of Pulsed ESPI
As noted above, in-situ time-effective inspection for residual lifetime assessment of social infrastructure facilities being developed and further improvement will be urgently required. To have accurate residual lifetime assessment, optical inspection using laser is one of the most useful options. Furthermore, two stage inspection improves time effectiveness and accuracy. In two stage inspection, the first is a full-field inspection for flaw screening and the second details flaw sizing. The first stage screening inspection rapidly detects nontrivial flaw locations. In this work, the author undertook full-field inspection with pulsed ESPI using laser. The laser induced ultrasonic test method called laser UT has been already much studied at many plant manufacturers,2) but full-field inspection using pulsed ESPI has not been used previously. Surface cracks on thick plate can be detected by pulsed ESPI inducing surface shockwaves. Conventional inspection using ESPI for aircraft maintenance is detected by cyclic vibration induced by the shaker and it is practical only for flexible CFRP (Carbon Fiber Reinforced Plastic) rotors, aluminum body plates and so on. But there are many requirements to inspect for flaws in stiff and thick plate. Considering nuclear power stations, the Rules on fitness-for-service for nuclear power plants3) were issued in May 2000 by JSME (Japan Society of Mechanical Engineers) S NA1-2000 and from 2002 they were gradually promoted for aged nuclear power plants. Full-field inspection using pulsed ESPI offers remote sensing and more than 500 mm square inspection at a glance. It detects the location of nontrivial flaws for following up with detailed sizing inspection as shown in Fig. 1.

2.2 Newly Undertaken Full-field Inspection
Full-field inspection is essentially a screening inspection used for speed, and in conventional in-situ inspection, screening resolution and screening time were thought to be a trade-off. But if optical full-field inspection is applied, screening resolution and screening time are not traded-off because the optical full-field

Fig. 1 Flow of full-field inspection.
sensor is sensing remotely and scanning velocity is not a time issue when a galvano-mirror is used. The galvano-mirror is at some distance from the target so scanning by the optical beam requires minimum mechanical motion and time. Furthermore, optical full-field inspection takes the flaw location as two dimensional digital image data. So it can collect two dimensional image data of flaw locations and sizes over more than a meter square at the same time. Also screening resolution will cut off trivial flaw data. This convenience comes from the rapid improvements currently being made in digital image data processing time. These attractive points will make the full-field inspection the best option for time- and cost-effective in-situ flaw-screening method. In USA, the concept of Risk Based Maintenance (RBM) is gradually becoming accepted as a qualitative risk-assessed maintenance guideline. Already API (American Petroleum Institute) and ASME (American Society of Mechanical Engineers) have promoted it on their petroleum plant and fossil plant boilers. The frequency and financial damage of each accidental event for main components has been assessed quantitatively taking into account age and in-situ inspection periodicity. These qualitatively assessed entities are plotted on a financial risk ranking-diagram shown in Fig. 2. Looking at this diagram, plant operators utilities should make efforts to reduce financial risk by practicable improvement procedures. Financial risk rank is divided into four grades; Acceptable, Acceptable with control, Undesirable, and Unacceptable. These rankings are determined from the financial consequence multiplied by event frequency. When the risk is hardly definable in financial consequence, safety consequence is applied and considered on a similar diagram shown in Fig. 2 (b). The unacceptable events in these diagrams should be decreased in financial consequence or event frequency as a top priority using monitoring, shorter-cycle inspection, repairs, remaking, redesigning and so on. Any financial risk improvement option should, however, be assessed for the scale of financial risk reduction compared with the cost of making a improvement. The author believes that the RBM concept will be applied even in nuclear power generating plant maintenance in the near future and at that time pulsed ESPI full-field inspection will support it strongly.

3. Full-field Demonstration Test Results

In our in-situ inspection for electric power generation plant, surface breaking Stress Corrosion Cracking is most important and a flaw that must be detected. In thick stainless steel plate inspection, conventionally, ultrasonic inspection is used with the ultrasonic transducer attached to a material surface and scanned longitudinally and transversely. To improve the cost- and time-effectiveness of in-situ inspection, laser induced ultrasonic inspection has been applied. However, the author proposes pulsed ESPI for full-field SCC-inspection rather than the laser induced ultrasonic inspection. Full field inspection saves considerable time and money before resorting to detailed ultrasonic inspection. To detect surface cracking on thick plate more than 20 mm, pulsed laser holography called pulsed ESPI, was applied in this study. Pulsed ESPI inspection, also known as laser shearography, has been applied on flexible metal plate and flexible CRFP components, such as airplane skins and rotors of helicopters. But the author conducted the first trial of pulsed ESPI for surface crack inspection in very stiff thick plate in 1990s. To detect surface cracking on thick plate, Rayleigh waves, shear wave propagating surface, were used instead of P-waves (longitudinal wave). The experimental setup is shown in Fig. 3. The difference between two speckle pattern images makes a surface displacement contour as shown in Fig. 4. An example of the enlarged wave-reflected-contour image at the crack is shown in Fig. 5. As the Rayleigh wave propagates, a contour of the wave front propagates from the center of the plate to the outer edge. From these image movements the Rayleigh wave traveling velocity was determined to be around 3000 m/sec, which is a theoretically reasonable value. In these experiments the author used a falling steel ball to induce sonic waves, but it was very hard to make accurate trigger timing because of low repeatability. The dimension of specimens was 500 mm × 500 mm × 20 mm and the diameter of the steel ball was 15 mm. The
detectable flaw size taken from experiments is shown in Fig. 6. From these results the detectable crack depth was more than 2 mm. From our experimental results, crack edge deformation was proportional to crack area. Volumetric strain energy caused by out-of-plane deformation, $\Delta H$, at the crack edge is proportional to strain energy, $\Delta U$, induced by wave reflection. If both in-plane and out-of-plane strains are assumed to be same ($\epsilon$), $\Delta U$ is given by the equation (1). In such a relationship, the detectable crack size is defined by crack area shown in Fig. 6. From this figure crack depth sizing is possible from analyzing the wave reflected contour. This should be a very attractive point when using RBM.

\[
\Delta U = F \times \Delta H = \sigma \times \Delta \times \Delta H = \epsilon E \times \Delta V
\]  

(1)

4. Simulation of Shock Wave Propagation

4.1 Finite Difference Method for Sonic Wave

To simulate sonic wave propagation on thick steel plate, there are two options, one is Finite Element Method (FEM) analysis and the other is the finite difference method. The author used an implicit scheme finite difference method for both time and dimensional mesh size. The implicit scheme of the finite difference method is calculated by simultaneous equations and it performs well in numerical stability. Yamawaki in NIMS (National Institute for Material Science) developed finite difference method code ten years ago to analyze laser-induced ultrasonic propagation in anisotropic crystallized material and the code was used for the simulation of shock wave propagation on a steel plate surface by the author. The two dimensional equation of elastic wave propagation is given as follows; $x$-$y$ being solved by the finite difference method. Here $U$ is $x$-directional displacement and $V$ is $y$-directional displacement, and $F$ is volumetric force.

\[
\rho \frac{\partial^2 U}{\partial t^2} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + F_x
\]

(2)

\[
\rho \frac{\partial^2 V}{\partial t^2} = \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + F_y
\]

(3)

Here, $\rho$: material density [kg/m$^3$], $F_x$: $x$-direction volumetric force [N/m$^3$], $F_y$: $y$-direction volumetric force [N/m$^3$], $T_{xx}$, $T_{yy}$, $T_{xy}$: Stress [N/m$^2$].

Strain is calculated by the center-weighted finite difference method as follows and these are implicit scheme.

\[
S_u = \frac{\partial U}{\partial x} = \frac{\left[ (U_{i+1,j} - U_{i-1,j}) - (U_{i,j+1} - U_{i,j-1}) \right]}{2L}
\]

(4)

\[
S_v = \frac{\partial V}{\partial y} = \frac{\left[ (V_{i+1,j} - V_{i-1,j}) - (V_{i,j+1} - V_{i,j-1}) \right]}{2L}
\]

(5)

\[
S_{xy} = \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}
\]

(6)

$X$ and $y$-directional shear stresses were given as follows using strain calculated by Eq. (7), (8) and (9). $C$ is the elastic coefficient here.

\[
T_{xx} = C_{11} S_{xx} + C_{12} S_{yy}
\]

(7)

\[
T_{yy} = C_{11} S_{yy} + C_{12} S_{xx}
\]

(8)

\[
T_{xy} = C_{13} S_{xy}
\]

(9)

From these Eq. (2) to (9), the author simulated shock-wave propagation on thick steel plate using a center-weighted implicit finite difference method.

4.2 Simulation of Slab Model with Crack

A two dimensional slab model with a surface slit-like crack
was used to simplify the complicated shock wave reflection mechanism shown in Fig. 8. This model was an infinite slab in the z-direction. The Rayleigh wave velocity of about 3000 m/sec in this simulation compared reasonably with experiments. To simulate several MHz wave propagation, the time step width and dimensional mesh scale are optimized appropriately to describe the phenomena. The time mesh was 25 nsec and dimensional mesh was 0.4 mm both in x and y direction. A P-wave was induced at a location on the upper surface, 40 mm to the left side of the crack edge, and a cylindrical P-wave propagated through the material and reflected on the bottom surface. The initial vibration force was a sinusoidal 1/4 wave with frequencies of 100 kHz and 500 kHz, and peak force of 1 Pa. In this simulation the peak force is not such an important value because this analysis is a qualitative demonstration of the experimental principles, not a quantitative one. Two dimensional cylindrical wave propagation in this model can not simulate three dimensional spherical wave propagation quantitatively. Generally speaking, higher frequency detects smaller defects because of its smaller wave length, and the author proposed to demonstrate these phenomena by comparing results from two different frequencies. The material was conventional steel and the elastic coefficient of steel was used for this simulation.

An initial vibration wave of 100 kHz propagates through a two dimensional slab plate as a cylindrical wave front as shown in Fig. 9. The wave induction point was 40 mm left from the surface crack location. Fig. 9 and Fig. 11 show the wave reflection at the crack. Fig. 11 shows a five-times shorter wave (500 kHz) and displacement image is clearer than in Fig. 9 (100 kHz). The surface wave velocity is two thirds of the P-wave velocity of 5000 m/sec. The surface wave propagating delay compared with the P-wave is shown both in Fig. 9 and 11. The surface wavelength at 100 kHz is 30 mm and 500 kHz is 6 mm, one fifth of that of the 100 Hz wave. Wavelength difference can be shown as relative surface displacement shapes, Fig. 10 and 12. The 100 kHz surface wave reflection had smoother surface displacement compared with Fig. 12 (500 kHz). This out-of-plane displacement could be detected as a pulsed ESPI speckle pattern and the crack edge discontinuous displacement was displayed at the ESPI contour image. The author demonstrated that pulsed

Concerning the simulated out-of-plane displacement, discontinuity of the contour image of the ESPI experiments is caused by surface displacement in y-direction and contour discontinuity over time. That means there are many harmonic shock waves induced, especially in the higher 500 kHz, and these, in turn, induce crack edge discontinuous displacement in the y-direction. Some harmonics are reflected at the crack edge and tip, and some pass through the crack tip. These complicated displacements give rise to the ESPI contour discontinuity.

4.3 Surface Wave Simulation on a Welded Deposit

Almost all components of electricity generation plant are constructed by welding and weldments are often prone to cracking

![Fig. 8 2D-finite difference method model of ultrasonic.](image)

![Fig. 9 Simulation results induced by 100 kHz.](image)

![Fig. 10 Simulation results of relative displacement (100 kHz).](image)
problems with age. The weld bead is uni-directionally crystal-
lized metal and the diffractive coefficient is different from the 
substrate metal. Volumetric P-waves are reflected and refracted 
at the boundary surface of weld deposits. Indeed these ultrasonic 
wave reflections and refractions make in-situ inspection work very difficult and they are serious problems for NDT (Non-
destructive Test) technicians. Reflected echoes from the crack 
and from the weld bead boundary surface must be differentiated 
by NDT technicians. In such circumstances, the author proposed 
to simulate surface wave propagation at the weld deposit bound-
ary line. From many experimental results surface wave propa-
gation was less influenced by the weld bead boundary line com-
pared with disturbance of the volumetric P wave at the bead 
boundary surface. To confirm the validity of simulated results,

The author calculated P-wave propagation in uni-directionally 
crystalized infinite metal. In anisotropic austenite steel the P-
wave, the shear horizontal wave (SH-wave) and shear vertical 
wave (SV-wave) propagate by the velocity distribution shown 
in Fig. 13 at (100) plane\(^1\) as a slowness curve of inverse phase 
velocity. These simulation results show the validity of the aniso-
 trope elastic modulus matrix. To confirm the validity of the 
simulation results, the following conditions were applied in the 
finite difference code.

a. X- and y-directional mesh both 0.4 mm
b. Time resolution span 25 nsec.
c. Material elastic modulus was taken from Ni's.
d. Initial vibration was 2 times sinusoidal wave of 0.5 \(\mu\)sec cycle, 
amplitude was 1 Pa.
e. Initial loaded direction was \((x, y, z) = (1, 1, 1)\)
The elastic modulus matrix was given as follow.

\[
C^\prime = \begin{pmatrix}
2.87 \times 10^2 & 1.55 \times 10^2 & 1.16 \times 10^2 & 0 & 0 & 0 \\
1.55 \times 10^2 & 2.48 \times 10^2 & 1.55 \times 10^2 & 0 & 0 & 0 \\
1.16 \times 10^2 & 1.55 \times 10^2 & 2.87 \times 10^2 & 0 & 0 & 0 \\
0 & 0 & 0 & 1.24 \times 10^2 & 0 & 0 \\
0 & 0 & 0 & 0 & 8.54 \times 10^2 & 0 \\
0 & 0 & 0 & 0 & 0 & 1.24 \times 10^2 
\end{pmatrix}
\]

The simulation result of displacement is shown in Fig. 14. From 
the results, we can see that y-directional crystallization gave the 
anisotropic wave propagation a much deformed wave front and 
demonstrated that this simulation code is valid even in anisotro-
pic material. The sonic velocity parallel to the crystallized di-
rection is faster than the velocity vertical to the crystallized di-
rection, and it was demonstrated that wave front shapes deformed 
to become oval not spherical. Acoustic wave propagation in the 
welded austenitic stainless steel plate was simulated by the two 
dimensional slab model shown in Fig. 15. The weld metal was a 
y-directionally crystalized model. Its width was 16 mm and 
thickness 32 mm, taken from our welded specimen. Initial vi-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig11.png}
\caption{Simulation results induced by 500 kHz.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig12.png}
\caption{Simulation results of relative displacement (500 kHz).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig13.png}
\caption{Slowness curve of anisotropic metal at (100) plane.\(^1\)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig14.png}
\caption{Wave-front displacement in anisotropic metal.}
\end{figure}
vation was induced at the location 16 mm left of the welded boundary. The simulation results are shown in Fig. 16. The induced wave propagates with a spherical wave front and reflected at the weld deposit boundary. After passing through the boundary, the spherical wave front is much deformed into the weld bead because of the directional diffraction index. But looking at the surface acoustic wave (SAW) propagation there is no significant reflection and deformation. This attractive point makes SAW suitable for inspection of flaws near a welded area.

5. In-situ Flaw Sizing Using Laser UT

After the full-field screening inspection for flaw location and rough sizing, detailed flaw sizing is required for each flaw location. The author undertook laser induced ultrasonic inspection (Laser UT) for detailed crack sizing. Laser UT measures crack depth and length by the time of flight method (TOF). As an example, the allowable flaw size in nuclear power plant is defined in the rules on fitness-for-service for nuclear power plants (JSME S NA1-2000). The author tried to measure surface crack depth sizes by laser UT using TOF. But austenite stainless steel’s grain size was more than 50 mm, and the weld deposit had yet further larger grain size and was directionally crystallized. These metallurgical characteristics give a low S/N ratio ultrasonic pulse echo and unexpected echoes were received from grain boundaries and crystallized weld metal. In austenitic stainless steel almost all surface cracking is located near to weld deposits and this often confuses TOF results. Nuclear and fossil power plant use alloy-800 for high temperature resistance. Alloy-800 has even larger grain size than austenitic stainless steel and displays anisotropic crystallization even in the base metal. These metallurgical characteristics make it even more difficult to take valid ultrasonic pulse echoes compared with austenitic stainless steel. The author considered these difficult problems could be tackled using wavelet transformation. Using an optimized initial wavelet frequency, the received S/N ratio of the echo was marginally improved, but it would take too long to achieve satisfactory accuracy for the author. At that time Ochiai et al were attempting crack depth sizing by spectrum analysis of pulse echo that passes the crack, Fig. 17. The wave passing through the crack tip has a longer wavelength spectrum compared with the crack depth received by the laser-vibrometer. A typical result found by Ochiai et al is shown in Fig. 18. In the figure the ‘with-slit’ spectrum has passed through the crack tip and the ‘no-slit’ spectrum has arrived directly. The ‘with-slit’ spectrum is clearly attenuated in frequencies lower than 2 MHz. This measuring method gave satisfactory crack-sizing accuracy and S/N ratio even in alloy-800 and austenitic weld metal. An in-situ inspection of PWR pressure vessel bottom nozzles were successfully carried out in early 2005 with this technique. This confirmed the author’s thoughts that crack sizing should be possible by this spectrum attenuation method.

6. In-situ Application of Pulsed ESPI

6.1 Inducing Surface Waves

Shock wave propagating contour detection using pulsed ESPI was studied by Pedrini and Tinziani in 1990s and shock wave propagation on 15 mm thick steel plate was visualized using a double-pulsed ruby laser with speckle pattern analysis. But they did not address NDI applications of thick plate. Their paper reported surface shock wave visualized as circular contour propagation from the center to the edge of the specimen. The author tried a feasibility experiment for surface crack detection at 20 mm thick steel plate using a pulsed ruby laser. But, at that time, to get accurate trigger timing was very difficult and it took more than a day to take satisfactory image of crack reflection. The author used a steel ball falling on the specimen to induce initial surface waves in the same way as Pedrini and Tinziani. It is a
low cost method to induce surface shock waves with satisfactory repeatability, but it was very hard to have accurate trigger timing. After the results, the author’s group secured financial assistance from MITI (Ministry of International Trade and Industry) from 2000 for 5 years. The target of the work was in-situ nuclear plant maintenance application and this required underwater operation. So our group used a pulsed green beam using the second harmonic wave of a YAG laser to reduce underwater beam attenuation, the beam wavelength was 532 nm. Pulse width was around 5 ns pulsed beam energy was around 100-300 mJ. The author’s group put considerable effort into producing repeatable initial waves on steel plate using accumulated piezo-electric elements and a laser of more than 500 mJ with longer pulse width. To avoid surface damage by laser ablation, a burst pulsed wave was applied. The pulsed laser induction of a sonic wave was very suitable for stringent trigger timing accuracy but weak points were its unsatisfactory wave amplitude and the risk of laser ablation damage on the substrate. Fig. 19 shows the experimental result using pulsed laser induced surface-shock waves.

6.2 Concept of In-situ Inspection

The simulation results on weldments of surface acoustic waves showed that they are hardly disturbed by either the weld boundary line or the weld metal compared with P-wave. It is known that, generally, almost all cracks are located near or in weld metal, but P-waves are reflected and refracted by weld metal deposits. So using surface waves for screening flaw inspection of weld structures is very reasonable. In the latter half of the 1990s, the author suggested two stage inspection with both full-field and detailed inspection using pulsed laser interference as shown in Fig. 20. As noted above, in underwater in-situ inspection, the second harmonic beam of a YAG laser can be used because it suffers less attenuation in water. The YAG laser second harmonic is a visible green beam and this would help to keep the safety of in-situ workers. Recently Etoh et al and Shimadzu Corp. developed an ultra-high speed camera capable of 1 million frames per second with a buffer memory store of 100 frames. Its fastest shutter time span is 250 nsec. From our work, we can see that the surface wave would propagate 3 mm per frame and would travel 0.75 mm during the shutter time span. Thus the 100 frames buffer memory would take 300 mm of slow-motion wave run provided it was sufficiently illuminated. This would realize full-field flaw inspection using slow-motion surface wave propagation, but sufficient illuminating laser for 100 shots will be required.

7. Conclusions

a. Demonstration experimental results of the pulsed ESPI and simulation of surface wave propagation suggest that pulsed ESPI

Fig. 19 Laser induced shock wave.

References