Computer simulation of ultrasonic testing for aerospace vehicle.

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Abstract. Non-destructive testing techniques are developed to secure reliability of aerospace vehicles used repetitively. In the case of cracks caused by thermal stress on walls in combustion chambers of liquid-fuel rockets, it is examined by ultrasonic waves visualization technique developed in AIST. The technique is composed with non-contact ultrasonic generation by pulsed-laser scanning, piezoelectric transducer for the ultrasonic detection, and image reconstruction processing. It enables detection of defects by visualization of ultrasonic waves scattered by the defects. In NIMS, the condition of the detection by the visualization is investigated using computer simulation for ultrasonic propagation that has capability of fast 3-D calculation. The simulation technique is based on finite-difference method and two-step elastic wave equations. It is reported about the investigation by the calculation, and shows availability of the simulation for the ultrasonic testing technique of the wall cracks.

1. Introduction
Various nondestructive testing methods are examined for the reliability evaluation of structures for the space. Development of health evaluation method before and after the rocket use is a current target for the liquid-fuel rocket repetitively used. One of the developments is about non-destructive inspection for the combustion chamber of the liquid fuel engine. Inner wall of the chamber is affected by severe stress/thermal environment, and it may causes thinning and cracking of the wall[1,2]. As shown in figure 1, the wall has small channels where liquid hydrogen flows, and is made with Cu-alloy. The thinning occurs at the thin wall between the inner surface and the channels. Following the thinning, crack initiation and its growth occurs. Small defects of the combustion chamber may lead to severe accident of the rocket, so that precise investigation of the wall is required.

Figure 1. Schematic of wall of the combustion chamber. Upside is the inner surface. Repetition of combustion gas pressure and thermal stress causes deformation of the indicated area. Crack occurs from inside surface of H2-channel. Thickness of the area is around 1mm.
For the purpose, non-contact visualisation technique of ultrasonic propagation developed in AIST[3,4] is examined. The technique is composed with non-contact ultrasonic generation by scanning pulsed-laser with weak power, a position-fixed piezoelectric transducer for the ultrasonic reception, and image reconstruction process based on reciprocity theorem. The image reconstruction by reciprocity theorem gives the animation as if the ultrasonic surface waves and/or Lamb waves spread from the transducer along specimen surface. Existence of defects located near surface can be recognized as scattered surface/Lamb waves in the animation.

In parallel with the experiment of the imaging, the computer simulation of the visualisation was examined. Computer simulation of ultrasonic propagation is expected as tool for analysis and investigation of experimental condition. In this report, the computer simulation for the NDT of inner wall of the combustion chamber is described.

2. Computer simulation method

The calculation method[5] for ultrasonic propagation is based on the finite-difference method. The method uses 2-stages elastic wave equations composed with two independent variables of $v$: particle velocity and $T$: stress, as shown in eq.(1)[9], where $\rho$: density, and $C$: stiffness matrix. Originally, the 2-stages equations are used in FDTD[7] and EFIT[8] methods. Difference between the method and FDTD/EFIT exists on discretized elastic material models. Figure 2 shows the model used in the previous technique of NIMS[6], and is also used in the new technique used here. This model gives easy interpretation of calculated results, and easy applicability for combined materials. Benefits of employment of eq.(1) were clarified by actual calculations as improvement of calculation speed, calculation stability at boundary, and applicability for air-coupled ultrasound.

Calculation model of the wall in figure 1 is constructed using combination of the unit cubes shown in figure 2. Each unit cube owns density and stiffness matrix of Cu-alloy. Crack is constructed as vacancy of unit cubes. Size of unit cube (spatial step) and duration of time step are determined by the same way as the finite-difference method.

\[
\rho \frac{\partial v}{\partial t} = \nabla \cdot T \quad \frac{\partial T}{\partial t} = C \nabla v
\]

Figure 2. Discretized 3-D elastic material model for calculation. The corner points of each cube represents particle velocities, and the center point of each cube represents stress.

3. Two-Dimensional calculation for crack detection using surface wave

The surface wave (Rayleigh wave) propagates in surface layer of solid, and penetration depth of surface waves depends on the wavelength, so that it is suitable for detection of defects located near surface. By selecting frequency of surface waves, subsurface defects could be detected without disturbance of subsurface structure such as H2-channel grooves in figure 1. Figure 3 shows 2-D calculation model to verify reflection of surface wave from a subsurface crack (slit). Only 3 subsurface grooves structure in wall of combustion chamber is modeled for the simplification of the calculation. The wall thickness is equal to 2 wavelengths of surface wave. The surface wave is generated selectively by applying sinusoidal stress of three cycles in the manor of the phased array. The slit with one spatial step in width is installed from the groove side in center part of the second groove. The relation between intensity of reflected wave from the slit and depth of the slit was examined.

In figure 3, reflected surface wave by the subsurface slit is observed clearly. In figure 4, waveform observed near the slit (point B) shows waves of various modes generated on the slit, however only the wave of mode of surface wave propagates stably along the surface (point A). The graph in figure 4 shows that deeper (longer in depth) slit or shorter residual thickness at slit position.
gives stronger reflection of surface waves. Especially the shorter residual thickness than one wavelength of surface wave (>50% in the graph) shows larger increasing rate of the reflected surface waves. From these results, by selecting the appropriate wavelength of surface wave, even with complex subsurface structure such as the grooves, it is expected that the reflected surface wave from the crack can be distinguished, and there is a possibility of estimation of the depth of the subsurface cracks.

Figure 3. 2-D Calculation model of the wall with crack (slit), and visualization of ultrasonic waves (shown in displacement). Depth of slit is 80% of wall thickness. Wavelength of Surface wave is 50% of the wall thickness at the grooves. Model size is 1600 x 200 spatial steps.

Figure 4. Waveforms of incident surface wave and reflected waves calculated by the simulation (case of slit depth in figure 3), and relation between depth of slit and strength of reflected wave from the slit. Point A is on the surface of the generation area, and point B is on the middle surface between first and second grooves, in figure 3.

4. Three-dimensional calculation for visualisation of surface waves with cracks
Currently, transfer function of the receiving transducer is not taken into account in the calculation, so results obtained by the calculation are not perfectly corresponding to the experimental results. However, it is obvious that the ultrasonic visualisation technique of AIST and the computer simulation have high adaptability. Figure 5 shows 3-D calculation model for the wall. The new simulation method enables efficient 3-D calculation of ultrasound using personal computers.

Figure 5. 3-D Calculation model for the wall with grooves and slit. Plane surface wave propagates toward to area with a subsurface slit. Model size is 720 x 300 x 100 spatial steps.
Snapshots of ultrasonic displacement at the surface. Three cycles sinusoidal surface wave propagates. Wavelength of the surface wave is equal to the wall thickness (0.8mm), and depth of the slit is 50% (0.4mm) of the thickness. After the surface waves, various scattered waves by grooves are observed in left images. Right images are obtained by image subtraction between images with the slit and without it. Scattered waves by the slit are selectively observed by the subtraction.

In figure 6, existence of slit is recognized clearly by the deformed wave front. In this case, wavelength of the surface wave is large in comparison with wall thickness, so that scattered waves by the grooves are remarkable. In the actual experiments, signal processing to eliminate progressive wave is performed. By the processing, effect similar to the image subtraction in figure 6 is performed.

5. Conclusions

By the computer simulation for ultrasonic propagation, it was clarified that the non-contact visualisation technique of ultrasonic propagation is effective for the defect detection of combustion chamber of liquid-fuel rocket. Also enhancement of detectability of defects by image processing was demonstrated in the simulation. It was confirmed that the simulation was effective to secure reliability of the rocket. It is expected wider application of the computer simulation for ultrasonic non-destructive testing.

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