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In-situ structural integrity evaluation for high-power pulsed spallation neutron source – Effects of cavitation damage on structural vibration

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A B S T R A C T

A double-wall structure mercury target will be installed at the high-power pulsed spallation neutron source in the Japan Proton Accelerator Research Complex (J-PARC). Cavitation damage on the inner wall is an important factor governing the lifetime of the target-vessel. To monitor the structural integrity of the target vessel, displacement velocity at a point on the outer surface of the target vessel is measured using a laser Doppler vibrometer (LDV). The measured signals can be used for evaluating the damage inside the target vessel because of cyclic loading and cavitation bubble collapse caused by pulsed-beam induced pressure waves. The wavelet differential analysis (WDA) was applied to reveal the effects of the damage on vibrational cycling. To reduce the effects of noise superimposed on the vibration signals on the WDA results, analysis of variance (ANOVA) and analysis of covariance (ANCOVA), statistical methods were applied. Results from laboratory experiments, numerical simulation results with random noise added, and target vessel field data were analyzed by the WDA and the statistical methods. The analyses demonstrated that the established in-situ diagnostic technique can be used to effectively evaluate the structural response of the target vessel.

1. Introduction

The high-power pulsed spallation neutron source in the Japan Proton Accelerator Research Complex (J-PARC) is one of the newest facilities in the world for research on materials and life sciences. The mercury spallation target comprises a mercury vessel surrounded by a water shroud, connected to each other by ribs. Pulsed proton beams (25 Hz, 1 μs pulse duration) are injected into the mercury to generate neutrons. Pressure waves are generated in the mercury due to rapid heat deposition [1,2]. The pressure waves propagate through the target vessel and generate cavitation bubbles in the mercury [1]. However, cavitation damage of the target vessel wall, is a crucial issue because the damage may drastically shorten the target vessel's lifetime. Cavitation bubble collapse close to the target vessel leading to pitting and erosion of the wall, and, pressure waves drive stress waves in the target vessel [3].

To mitigate the damage due to pressure waves and the cavitation, several techniques are being developed by the Japan Atomic Energy Agency (JAEA) under international and domestic collaborations [4–9]. One of the techniques is using a double-wall configuration at the beam window of the target vessel based on that used at the spallation neutron source (SNS) target at ORNL; the mercury flow channel with a narrow gap of 2 mm was made by adding an inner wall just inside of the beam window, as shown in Fig. 1. The narrow mercury channel has been effective in the SNS target. It is expected that the mercury flow accelerated by the narrow channel and the narrow gap itself can distort bubble growth-collapse behavior-orienting the collapse jet away from the vessel surface. Because the outer wall is protected by the inner wall structure against cavitation damage, damage to the inner wall is an important factor governing the target vessel's lifetime.

Cavitation damage is expected to accumulate on the inner wall [10,11]. If it is severe enough, the inner wall will fracture and be penetrated because of erosion damage. Vibration signals can be affected by the altered structure of the inner wall and penetrating cavitation damage [12], as shown in Fig. 2.

Severe damage due to cavitation erosion has been reported on the inner wall of the mercury target vessel of the SNS in the United States [10]. In the Japan Spallation Neutron Source (JSNS), similar damage to the double-walled mercury target vessel is anticipated at the same position. The dynamic responses of the target vessel caused by pressure waves were investigated to establish a

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Nomenclature

WDA	wavelet differential analysis
WDI	wavelet differential image
Img	wavelet image
f	Frequency Hz
t	Time s
I_a	Average WDI intensity
D	Damage diameter mm
$V(t,f)$	WDI intensity at time t and frequency f dB
SS_T	Total sum of square
n	Total number of samples
y_{ij}	*jth* sample value of the *ith* group
M	Sample mean of all samples
h	Number of samples in each group
$\bar{y}_i$	Sample mean of the *ith* group
X	Factor X that affects vibration behavior
Y	Factor Y that affects vibration behavior
SS_b	Sum of squares between groups of samples
SS_e	Sum of squares within groups of samples
SS_X	Sum of squares due to factor X
SS_Y	Sum of squares due to factor Y
D_X	Degree of freedom of factor X
D_e	Degree of freedom of within groups of samples
F	Calculated value of *F*-test
T	Calculated value of *t*-test
$\bar{y}_{i'}, \bar{y}_{j'}$	Modified sample mean of the *ith* and *jth* group
$S_{\bar{y}_{i'}, \bar{y}_{j'}}$	Standard error of the modified sample mean
$f(x)$	Random function of noise amplitude
A,-A	Maximum amplitude value of noise
c, d	Constants

structural integrity evaluation technique for the JSNS target vessel. A laser Doppler vibrometer (LDV) was installed on the target vessel as an in-situ diagnostic system, providing the advantages of an entirely remote and non-contact technique [13]. The aim of the current effort is to use the vibration data recorded by this system for determining the critical level of damage to the inner wall that would jeopardize the outer wall leak integrity.

In a previous study, dependency of dynamic responses of the double-walled target vessel on penetrated damage was investigated using a numerical simulation [14]. The Wavelet Differential Analysis (WDA) diagnostic technique, was developed to reveal the differences in vibration signals based on the amount of damage.

However, vibration signal damage dependency is usually garbled by noise that appears in lab-scale experiments and in field data obtained by LDVs during operation of the JSNS target. In the present study, building upon the WDA technique, two statistical methods, in particular, analysis of variance (ANOVA) and analysis of covariance (ANCOVA), were used to reduce noise in the LDV data.

2. Experiments

The electro-magnetic impact testing machine (MIMTM) was used to experimentally investigate the dependency of vibration behavior on damage [15]. Fig. 3 shows the schematic of MIMTM vibration measurement system. The mercury chamber has a diameter of 100 mm and height of 15 mm. Strong pressure waves were rapidly imposed onto plate specimens (60 × 60 × 2.5 mm) made of type 316L stainless steel (the same material as that of JSNS mercury vessel) and fixed to the chamber head by bolts. The pressure waves were generated by a 1-mm-thick stainless steel diaphragm connected to an electromagnetically driven striker. The gap between the specimen and the upper wall of the mercury chamber was fixed to 2.3 mm to simulate the double-walled structure of the target vessel. To simulate the penetrated cavitation damage on the inner wall, holes with diameters of 1, 2, 5, and 10 mm were cut at the centers of different specimens. Impulsive pressure waves were induced in mercury at a repetition rate of 1 Hz. The MIMTM pressure wave intensity was set based on prior

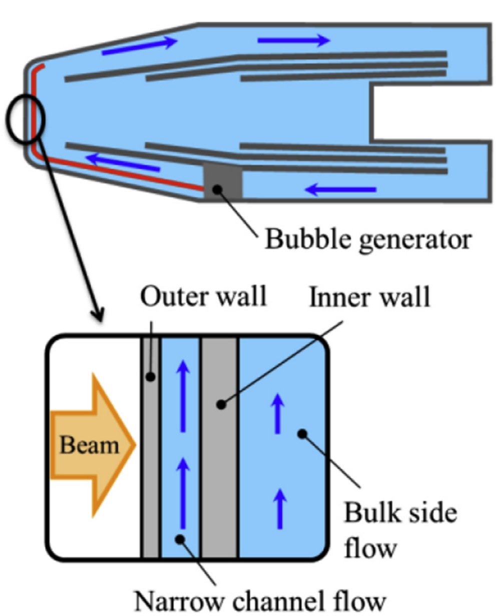

Fig. 1. Schematic of double-flow structure of beam window.

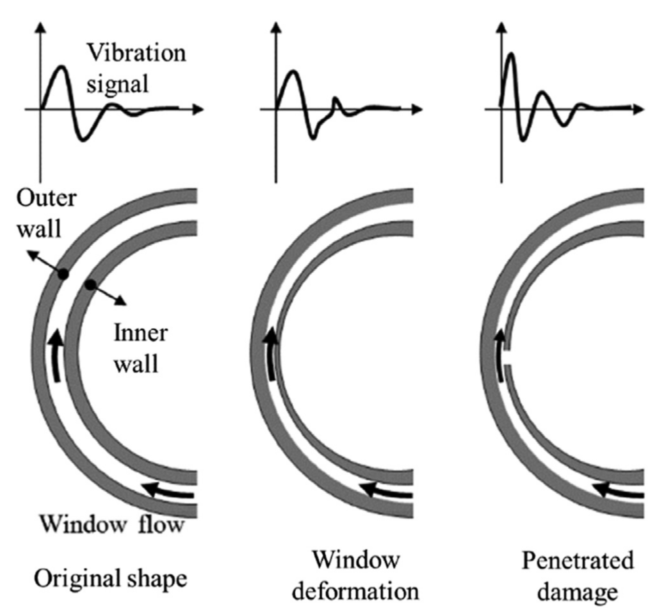

Fig. 2. Schematic of window deformation, damage scenarios, and target vessel vibration.