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Implementation of pressure wave mitigation and in-situ diagnostic of structural integrity for mercury target at MLF/ J-PARC

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Abstract. A liquid-mercury target system for a pulsed high power spallation neutron source is installed at at the MLF (Materials and Life science experimental Facility) in the J-PARC (Japan Proton Accelerator Research Complex). The moment the proton beams bombard the mercury target, pressure waves are generated in the mercury by thermally shocked heat deposition, which affects the structural integrity. The damage, so-called pitting damage, which is induced by the cavitation due to pressure wave propagation in mercury, is a critical issue to determine the lifetime and increase the acceptable proton beam power. Aggressive R&D has been carried out to understand and mitigate this phenomenon. As a result, a microbubbling system is recognized to be one of the most expectable techniques for the mitigation. In parallel, an in-situ diagnostic system is developed to evaluate the structural integrity. The vibrations of target vessel induced by the pressure waves were measured and the microbubbling was confirmed to be effective to mitigate the pressure waves.

1. Introduction

Neutrons are used for the innovative research that will bring about breakthrough in scientific and engineering research fields, i.e. fuel cell, hydrogen embrittlement, protein structure, medicine, etc. Mercury has the benefits for spallation neutron sources because of the high neutron yielding efficiency and usage as a coolant, and is available as target materials to produce neutrons by spallation reaction that is caused by the high-energy protons bombardment in mercury. The pulsed spallation neutron sources are being operated at the MLF (Materials and Life science experimental Facility) in the J-PARC (Japan Proton Accelerator Research Complex) in Japan [1] and SNS (Spallation Neutron Source) in US [2], which are standing on the way to increase the power up to MW-class. As increasing the proton beam power, the structural degradation due to fatigue and cavitation associated with the impulsive structural behavior is enhanced and gets to be a crucial issue: *i.e.* at the moment that the proton beam bombards in the mercury, thermal shock is generated in the mercury and the pressure waves are induced, whose amplitude is dependent on the proton beam power. On the process of the pressure wave propagation, aggressive cavitation generates in the mercury and imposes damage repeatedly on the solid wall of the target vessel. Therefore, the structural integrity is affected by the fatigue damage combined with cavitation. Theoretical and experimental investigations were carried out to understand the relationship between pressure wave conditions, mercury cavitation aggressiveness and fatigue damage growth behaviors on solid materials [3,4].

The in-situ diagnostic system on the structural integrity evaluation has been developed, which consists of a laser Doppler vibrometor, an impulsive sound microphone and a radioactive products detector. The laser Doppler vibrometor and the microphone were installed to investigate the dynamic responses of the target vessel [5]. The pressure waves excite the mercury target vessel and negative pressure that may cause cavitation along the vessel wall. The radiation detector is used to find pinholes resulting from the accumulated damage of fatigue combined with cavitation [6].

Gas-bubbles are injected into the flowing mercury to mitigate the pressure waves and suppress the cavitation inception [7]. The injected gas-bubble conditions were examined and the effects were predicted experimentally and theoretically from the viewpoints of microscopic and macroscopic time-scales, *i.e*. in the former is essential the pressure wave propagation process at the onset of proton beam injection, and in the later is dominant the interaction between the structural vibration and the pressure in mercury [8]. The relationship among the proton beam, the bubbling conditions and the pressure waves, which is very strongly related to the structural integrity of the target vessel, was investigated by the in-situ diagnostic system. Additionally, the numerical simulation on the dynamic response was carried out using LS-DYNA FEM code and compared with measured results.

2. Pressure wave and structural degradation

Figure 1 shows the target vessel for the spallation neutron source at the MLF/J-PARC. Mercury, which has high atomic number and is liquid at room temperature, has the benefits for pulse spallation neutron sources because of the high neutron yielding efficiency and usage as a coolant. The mercury target system consists of the target vessel and the mercury circulator which are installed on the target trolley [9]. The target vessel is filled with mercury circulating at *ca.*1m/s as flowing along by the beam window. The spallation reaction is induced when accelerated protons (1 MW, 3 GeV, 25 Hz, and 1 μs pulse duration) are bombarded in mercury and approximately a half of the power is dissipated for rapidly heating in mercury [10]. As a result, thermal shock occurs and generates the pressure waves in mercury. Temperature rising ΔT in mercury is given by

$$\Delta T = \frac{\Delta Q}{\rho c_v} , \tag{1}$$

where T is temperature, Q is heat density, c_v is specific heat capacity, ρ is density of mercury.
Pressure rising ΔP is given by

$$\Delta P = \beta_p K_T \Delta T , \tag{2}$$

where P is pressure, β_p is thermal expansion, K_T is bulk modulus.

Nuclear heat distributions ΔQ in the mercury target is very dependent on the proton beam profiles

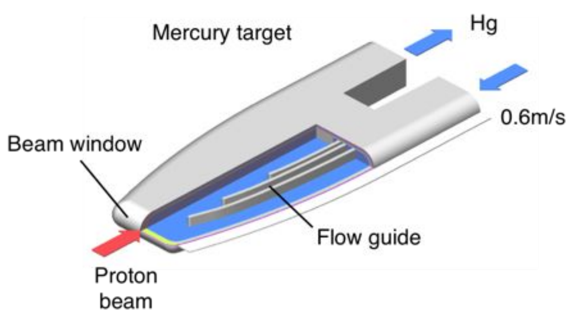


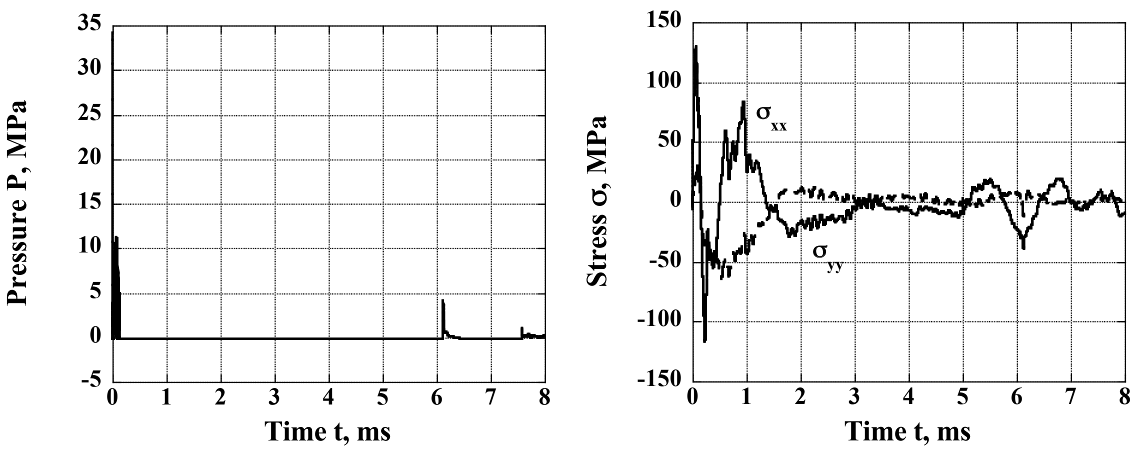
Figure 1 Mercury target at MLF/J-PARC. The drawing illustrates the inner wall of target vessel: *i.e*. the vessel consists of multi-wall structure to protect from the mercury leakage into the outside of vessel.

and the maximum peak pressure attributes to a peak heat deposition of beam profile. In order to investigate the pressure propagation and the dependency of pressure waves on the beam profiles, FEM analyses were carried out using an explicit code LS-DYNA [11]. Table 1 shows the element types and numbers used in the model consisting of the target vessel and mercury. The cut-off pressure model is applied to mercury to simulate the mercury failure due to cavitation. In the cut-off pressure model, a relationship between volumetric strain and pressure is assumed to be linear elastic when the pressure larger than the threshold, *i.e.* so-called the Blake threshold, whereas the mercury has no stiffness when the pressure is less than it. Actually, the threshold, *i.e.* liquid tensile strength, should be varied according to pressure rate as taking account of cavitation core growth that is dependent on the spinodal phenomena for phase changes between vapor and liquid [12]. Nevertheless, the cut-off pressure was assumed to be –0.15 MPa constant independently of the pressure rate as taking account of the numerical simulation efficiency. The boundary condition along the interface between solid wall and liquid mercury was tied.

Figure 2 shows the pressure time responses in liquid mercury nearby the beam window and the stresses imposed on the beam window under 1 MW power beam condition at the MLF/J-PARC. Nearby the window, the maximum pressure larger than 30 MPa is caused immediately after the proton beam injection with 1 μs pulse duration, and the longest period of negative pressure is 6 ms approximately as shown in Fig.2 (a), and then the pressure increases gradually after 8 ms. The negative pressure with a relatively long period is induced by the interaction between the solid wall and the presurre in mercury. The stresses imposing on the proton beam window are increased directly by the pressure wave collision agaist the beam window and excited by the interaction between the vessel

Table 1 Elements in FEM model of mercury target.

Structure	Element type	No. of elements	Material model
Mercury	8-node hexahedral solid	640,500	Bilinear with cut-off pressure
Target vessel	4-node tetragonal shell 8-node hexahedral solid	102,004	Linear elastic



(a) Time response of pressure (b) Time response of stresses

Figure 2 Time responses of pressure nearby the beam window and imposed stress on beam window.

wall and the mercury. The structural degradation due to the fatigue damage up to giga-cycles has to be considered, because the proton beams are injected into the target at 25 Hz throughout the lifetime of 5000 h which is defined in the target vessel design.

The other degradation factor related with pressure responses is cavitation damage, which is dependent on the cavitation bubble growth and collapse behaviors affected by the pressure wave time-response. The cavitation inception needs a certain negative pressure to grow the cavitation bubbles. The fatigue and cavitation damages are accumulated on the proton beam window which is a relatively thin wall structure and a critical part for the structural integrity. In fact, the radiation damage was taken into account to decide the lifetime in the target design: *i.e.* the steel ductility is likely to be degradaed by the accumulated radiartion dose that can be estimated by the radiation time and the proton beam intensity and energy. However, after reconizing the cavitation damage induced by the pressure waves, the fatigue combined by the cavitation got to be the most critical issue to realize the high power mercury target [14]. Therefore, in order to evaluate the structural integrity and keep the soundness, we developed the mitigation technique and the in-situ diagnostic system for the pressure waves.

3. Pressure wave mitigation by microbubbles

We are trying to inject microbubbles into the mercury to reduce the pressure waves and the imposed stresses and to suppress the cavitation bubble inception and growth [7] : *i.e.* the initial compressive pressure wave is reduced by absorption of the thermal expansion in mercury due to the contraction of microbubbles at the heat deposited area and at the onset of pressure wave propagation; during the wave propagation, the microbubbles can reduce the amplitude of the compressive pressure waves through attenuation of the pressure waves due to the thermal dissipation of kinetic energy and the dispersion. The cavitation inception is not dependent on the compressive pressure itself, and needs a certain negative pressure to grow the cavitation bubbles, *i.e.* so-called the Blake threshold. As assuming that the cavitation intensity is associated to the bubble size, the negative pressure period is essential to predict the damage. It is deduced numerically that the magnitude and the period of negative pressures resulting from the interaction between the intensive compressive pressure and the vessel wall and the inertia effect followed by the propagation of intensive compressive pressure waves are reduced effectively by the suitable bubble condition [14].

A bubbling element to establish the suitable bubble condition in flowing mercury; 50 μm in radius and 10^{-3} to 10^{-5} in void fraction, was developed and installed to the mercury vessel as illustrated in Fig. 3. The installed location was determined as taking account of the bubble distribution under flowing mercury, which was predicted by numerical simulation and experiments [15].

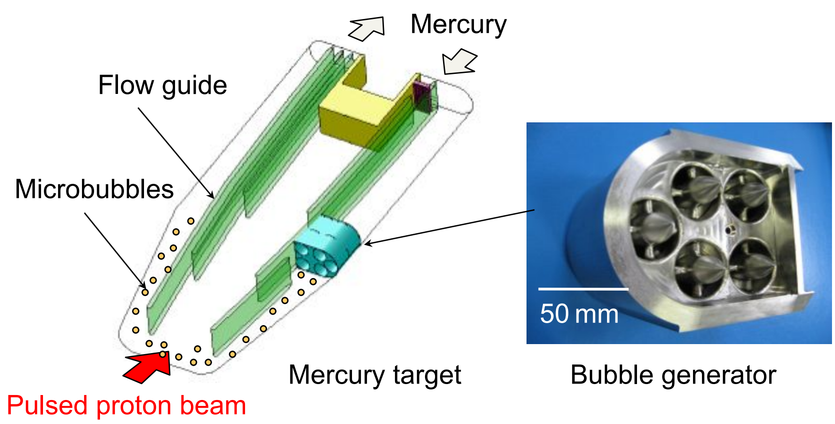


Figure 3 Pressure wave mitigation technique with microbubbles in merucry target.

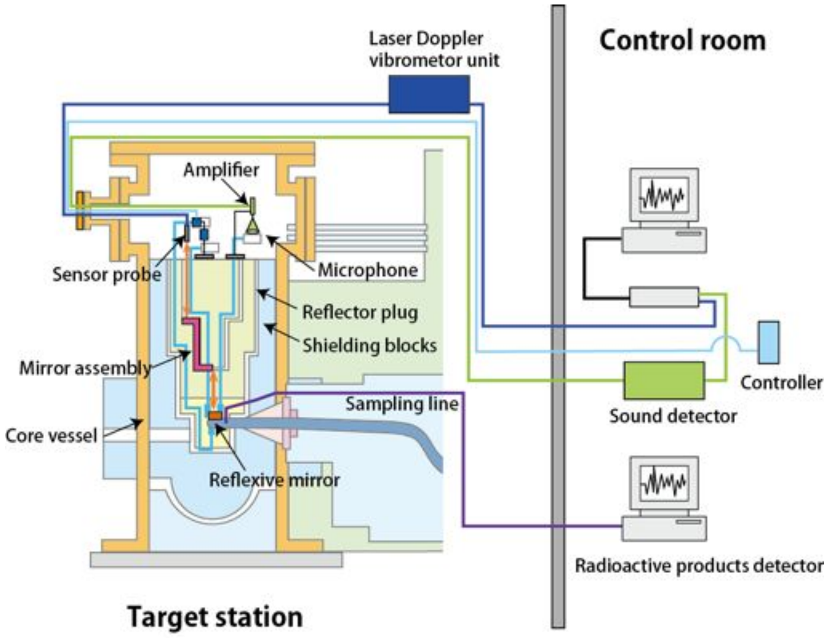
4. In-situ diagnostic system

The in-situ diagnostic system in terms of the structural integrity of the mercury target for the high power spallation neutron source at the target station in the MLF/J-PARC consists of three different concepts to add redundancy and enhance reliability: *i.e.* a laser Doppler vibrometor, a sound measurement and a radioactive products detector.

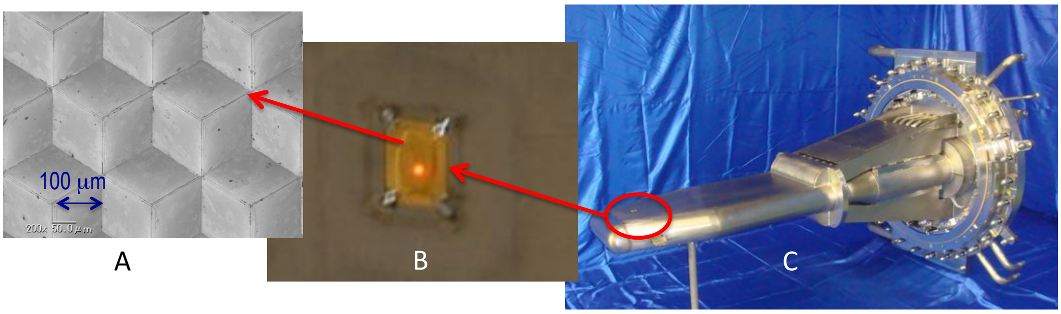
The laser Doppler system installed in MLF/J-PARC consists of the He-Ne laser generator (wavelength: 632.8 nm, power: 1.2 mW), the optical fiber (30 m), the X-Y stage, the mirror assembly, the reflexive mirror, etc. As illustrated in Fig.4, the laser beam was travelled through the optical fiber up to the X-Y stage fixed at the top of the reflector plug in the core vessel. The laser beam travels in the distance of 5 m through He gas atmosphere under high radioactive condition from the X-Y stage to the reflexive mirror fixed on the target vessel in the core vessel. The reflexive mirror was fabricated from a gold plate as taking account of radiation resistance and laser reflectance. The mirror surface was machined by using an advanced micro-machining technique to achieve a sufficient reflective efficiency. The micro-cutting reflexive mirror is shown in Fig.4 as well. The side of pyramid shape is 100 μm with a sharp corner, so that the reflection efficiency is more than 90 %, in the range that the allowable angle of the injected laser beam on the reflexive mirror surface is within ca 30 degree: *i.e.* the intensity of reflected laser beam is sufficient to measure the Doppler shift, even if the injection laser beam is inclined at 30 degree against the reflexive mirror surface.

A microphone with the frequency range DC to 20 kHz for the sound measuring system is installed around the position with about 5 m far from the target vessel. Because of the high radiation environment, there are the shielding blocks between the microphone and the target vessel to protect from radiation damage on the microphone. The atmosphere is filled with helium gas at a room temperature.

Additionally, the detection system for a pinhole-type failure due to accumulated cavitation and fatigue damages was developed as taking account of radioactive products in mercury. Two kinds of nuclei, ^{88}Kr and ^{122}Xe, that are originated in radioactive mercury and the most sensitive and distinguishable from the other radioactive products in terms of the steel vessel wall or the other components, were selected to detect the target failure with the pinhole-type failure penetrating through the vessel wall at the very early stage [6].



(a) Schematic drawing of in-situ diagnostic system on structural integrity of mercury target.



(b) Mercury target with reflexive mirror

Figure 4 In-situ diagnostic system of a pulsed high power neutron source at the MLF/J-PARC.

5. In-situ diagnostic system

Figure 5 shows the time-responses of displacement velocity measured at the upper wall of target vessel. The dynamic responses under various proton beam conditions were successfully measured under even high radiation condition by using remotely measuring system with the laser Doppler vibrometor. The relationship between the proton beam condition and dynamic responses was summarized as shown in Fig.6. The peak heat deposition was varied at 2, 4, and 5 J/cc by changing the beam profile. It was recognized that the dynamic behaviour is strongly associated with the proton beam power. The trend was confirmed numerically as shown in Fig. 7, which exhibits an adequate agreement with the experiment result shown in Fig.5. The most important part of the target vessel is the beam window because of the relatively thin wall, 2.5 mm in thickness, and severe loading conditions: combined static pressure with dynamic pressure due to pressure wave and thermal load due to proton beam heating. Figure 8 shows the relationship between the peak amplitude of displacement velocity at the upper wall and the imposed stress on the beam window. It is seen that there is the linear relationship between the velocity v at the upper wall and the imposed stress σ_d (Mises stress) on the beam window, and is described by the following equation:

$$\sigma_d = C\,v \qquad (3)$$

Note that the velocity is associated with the proton beam condition: *i.e.* energy, total power, beam profile, etc. Needless to say, C is dependent on the target vessel structure: $C=160$ *MPa/(m/s)* in the MLF/J-PARC target vessel. We can estimate the stress at the beam window readily by using Eq(3) and the in-situ measured velocity.

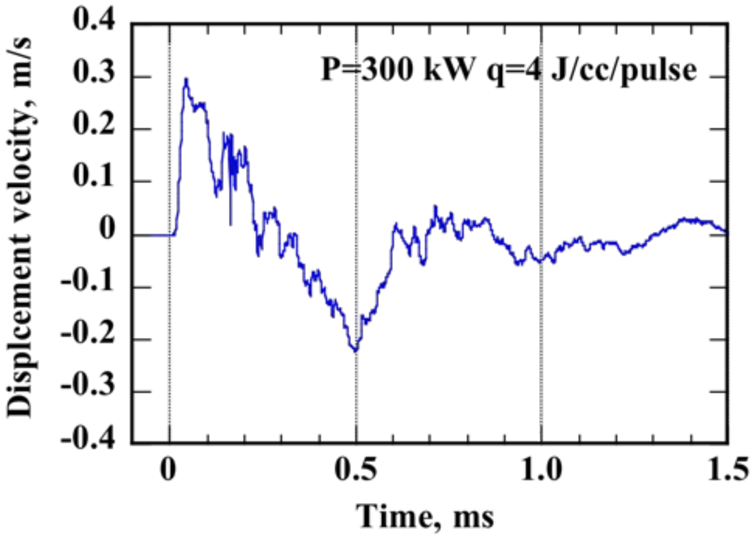


Figure 5 Time-responses of displacement velocity measured at the upper wall of target vessel.

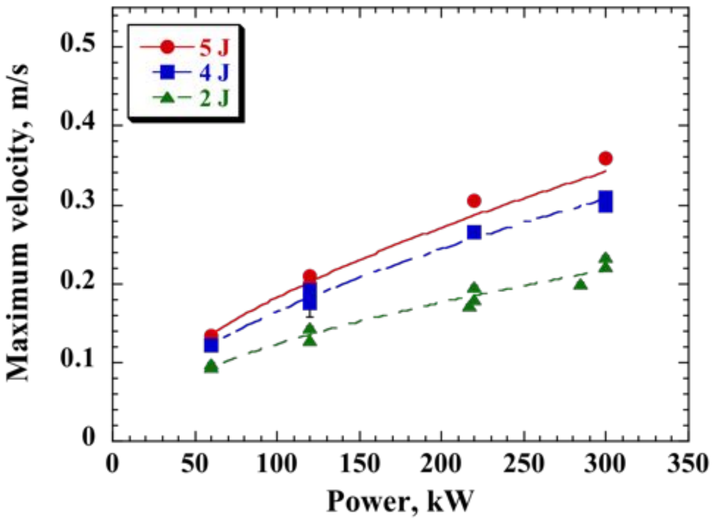


Figure 6 Relationship between the proton beam condition and dynamic responses.

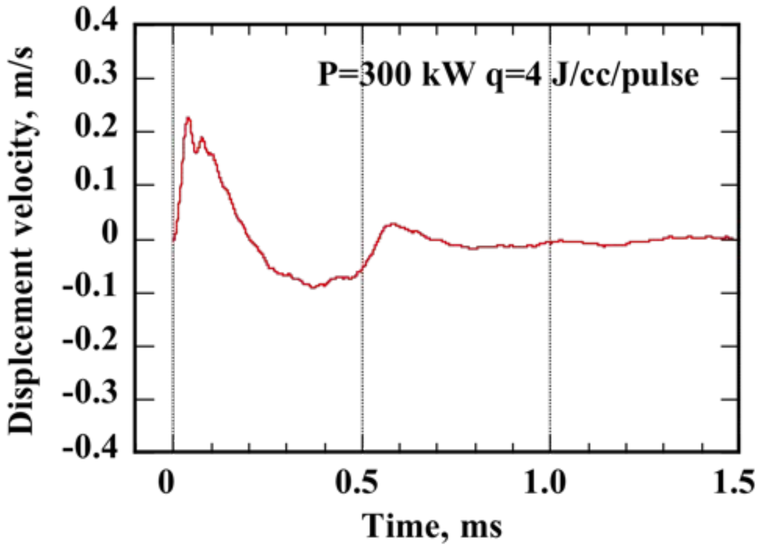


Figure 7 Numerically simulated dynamic response.

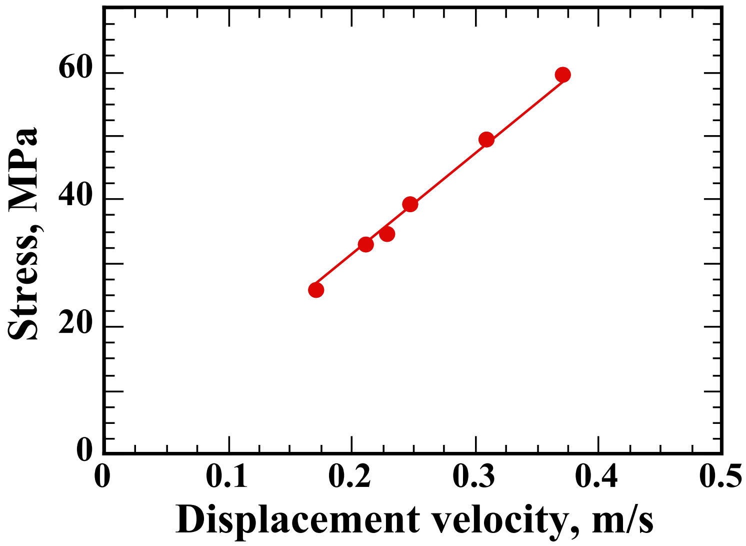


Figure 8 Relationship between displacement velocity and imposed stress on the beam window.

The stress increases definitely with the proton beam power and is estimated to be beyond the allowable design stress under 1 MW proton beam power with certain beam profiles [16]. In order to realize 1 MW power operation, R&Ds were carried out under international collaboration to mitigate the pressure wave imposing dynamic stress on the beam window. One of the most expectable technique is to inject micro-bubbles into the flowing mercury. Figure 9 shows the effect of microbubbles on mitigation of the displacement velocity, *i.e.* the pressure wave and the structural dynamic response were reduced by microbubbles. The amplitude with microbubbles gets to be less than a half of one without microbubbles. It can be said that the imposed stress on the beam window under the 1 MW operation is estimated to be lower than the allowable stress and the steady operation might be possible even under 1 MW beam power from the viewpoint of stresses evaluation if the microbubbles are injected into the flowing mercury continuously. It is found from the comparison between wavelet analyses on the velocities with and without microbubbles that the high frequency components beyond 20 kHz were damped immediately by the microbubbles. Cavitation bubble collapsing brings about excitation with high frequency components [7]. The cavitation damage is not unambiguous yet until the post irradiation examination, PIE will be carried out to look into the inside wall surface of the proton beam window. It is, however, expected that the cavitation damage is mitigated effectively because the pressure waves and the high frequency components are reduced certainly.

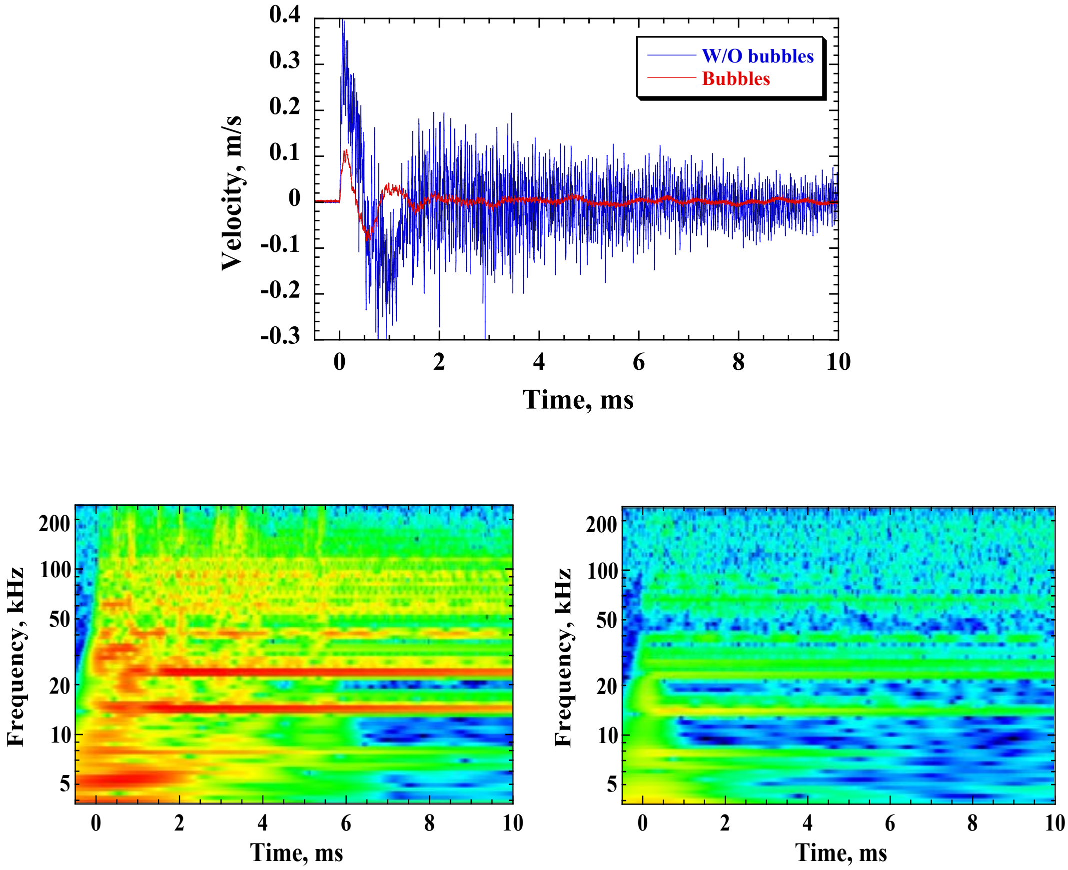


Figure 9 Effect of microbubble mitigation on pressure waves: time responses and wavelet analyses of displacement velocity under the condition with and without microbubbles.

Figure 10 shows the time responses and the wevelet analyses of sound measured under the condition with and without microbubbles. The bubbling effect is understandable clearly: *i.e.* the sound response induced by the proton beam injection was suppressed and the sound damping was enhanced by the microbubbles. The structural vibration affects the sound, which corresponds to the displacement velocity measured at the target vessel wall. The developed diagnostic evaluation technique based on the laser Doppler vibrometor and sound measuring system is suitable to detect the structural integrity related to the pressure waves which are induced by the high intense proton beams in the mercury target for the neutron source. The technique might be applied as the in-situ diagnostic system for structural integrity evaluation under ultimate environments in nuclear reactors and/or space station, etc.

The background of radiation is being evaluated to recognize the radioactive products originating from mercury throughout the operation. The data is being accumulated to detect the pinhole-type failure. Fortunately, up to now the signal related to the failure has not been recognized.

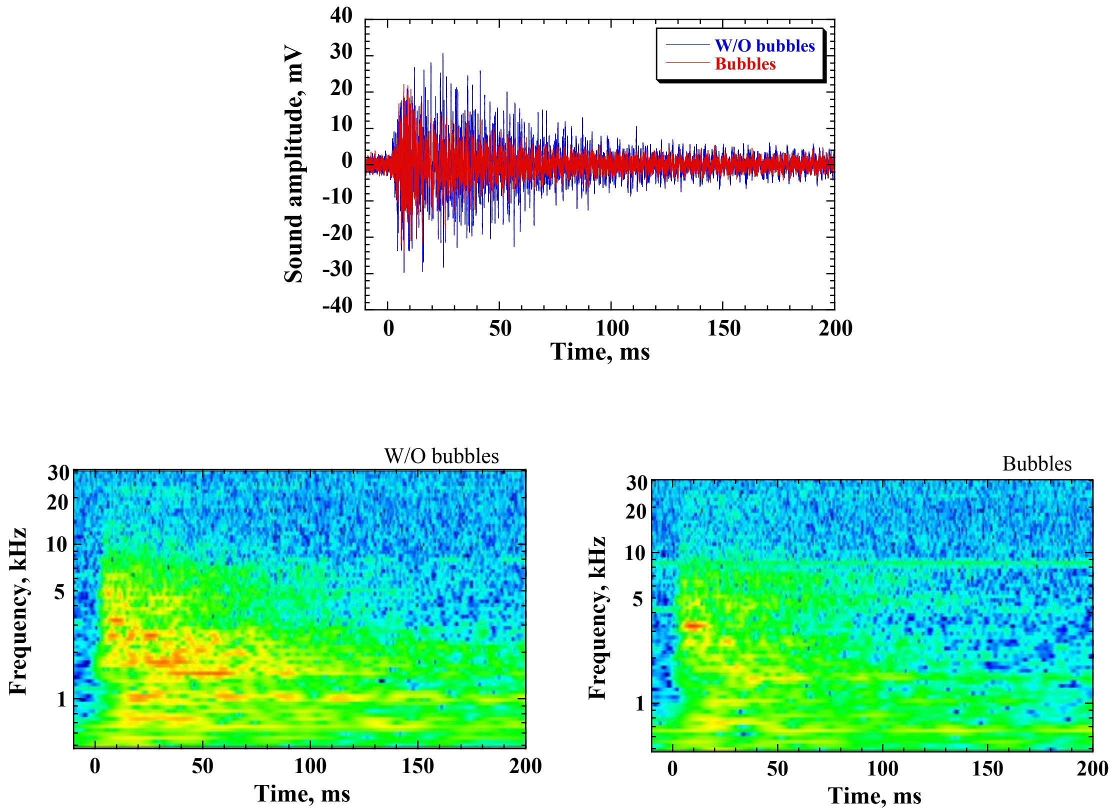


Figure 10 Effect of microbubble mitigation on pressure waves: time responses and wavelet analyses of sound under the condition with and without microbubbles.

6. Conclusion

A liquid-mercury target system for a pulsed high power spallation neutron source was installed at the MLF/J-PARC. The in-situ diagnostic system is embedded to evaluate the structural integrity related with the pressure waves induced by the high intensive proton beam bombardment. The system consists of the laser Doppler vibrometor, the sound measuring microphone and the radioactive products detector. The structural integrity is very dependent on excitation due to the pressure waves. Microbubbles are injected into the flowing mercury to mitigate the pressure waves and the mitigation effect was successfully confirmed by using the in-situ diagnostic system. The imposed stresses on the beam window under the condition with microbubbles were estimated to be lower than a half of ones without microbubbles. The developed in-situ diagnostic system is very useful to evaluate the structural integrity of the target vessel operating under extremely high radiation environments.

Acknowledgements

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