

Article

Image-Based Focus Retention Verification of a Commercial Optical Microscope Module in Launch Environments

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Abstract

Recent growth in space biomedicine has increased the need for compact optical microscope modules for biological observation under microgravity. In this study, two nominally identical commercial off-the-shelf (COTS) microscope units were evaluated under launch vibration and shock environments. One unit was mounted with a laminated viscoelastic passive vibration isolator, while the other was mounted without isolation. Random vibration and shock tests were performed to evaluate structural characteristics and focus retention. During random vibration, the non-isolated configuration showed high acceleration responses and clear focus degradation. In contrast, the isolated configuration reduced the overall acceleration response by up to 3.96 times and maintained a focus retention ratio above the study-specific screening threshold of 0.8. LLSS results and visual inspection showed no clear change in global structural characteristics or visible damage. After shock testing, both configurations remained above the same threshold with no marked focus degradation. Under the applied test conditions, broadband random vibration caused greater focus degradation than short-duration shock loading. These results indicate that image-based focus retention assessment should complement structural assessment when verifying COTS optical microscope modules for space biomedical applications.

Keywords: optical microscope; passive vibration isolation; focus stability; launch environments; space biomedical applications



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1. Introduction

Research on space bioengineering and pharmaceuticals, including space medicine, has recently expanded [1]. The space pharmaceutical manufacturing is also regarded as a space industry sector with a high ripple effect. In addition, synthetic biology research using microorganisms in the space environment to produce food and pharmaceutical materials has been actively conducted [2–4]. The satellites in orbit and the ISS (International Space Station) provide a microgravity environment of approximately 10^{-6} g. This environment affects various biological and material science phenomena such as cell differentiation, gene expression, and protein crystallization [5–8]. Gravity-induced phenomena such as buoyancy-driven convection, sedimentation, and phase separation are suppressed under microgravity conditions. Therefore, microgravity enables drug manufacturing processes

to overcome the limitations of conventional ground-based pharmaceutical processes [9]. Protein crystals and pharmaceutical materials formed in space have attracted significant attention because of their higher uniformity and structural stability compared to those produced on Earth. Scientific experiments using microgravity environments are currently being conducted on various platforms, including drop towers, space stations, and satellites [10]. However, drop towers have limitations in that the duration of microgravity is restricted to a few seconds. Therefore, the use of space stations and orbiting satellites has increased in experiments requiring longer test durations.

As these studies have expanded, the demand for optical microscope-based observation systems has also increased. These systems are required to precisely observe biological responses in space. Optical microscopes play an important role in biological research by visualizing cellular characteristics from subcellular organelles to tissue levels and by recording human cell types, states, and functions [11]. In particular, advances in optical imaging technologies have strongly supported large-scale global initiatives for mapping cellular diversity in human biology and disease, such as the Human Cell Atlas and European LifeTime Initiative [12–14]. According to the statistics of experiments performed at the ISS, life science research facilities and the Light Microscopy Module have been frequently used [15]. The Mochii microscope system operated by JAXA has established an on-orbit analysis system. Unlike the conventional approach, in which space-tested samples are returned to the Earth for analysis, Mochii directly analyzed samples in orbit and transmitted the results to the ground. This reduced the analysis schedule, which required several months [16]. These examples demonstrate the need for optical instruments that can measure real-time biological changes in a space environment. Thus, the demand for microscope systems is continuously increasing in the fields of space bioengineering and pharmaceuticals [15].

As the demand for microscope systems has increased, the use of partially modified commercial off-the-shelf (COTS) microscope systems as payloads has also increased to reduce costs and development time [17,18]. Although COTS microscopes are advantageous in terms of their cost and scheduling, they are designed for ground operations. Therefore, the verification data for launch vibration and shock loads are generally insufficient; in most cases, microscope manufacturers do not provide environmental specifications.

In microscope-based experiments, focus stability is a key performance index that is directly related to data reliability. Therefore, focus retention performance should be verified before the launch to ensure normal operation after launch. Space-based bioengineering and pharmaceutical experiments generally maintain an internal pressure of 1 atm by sealing payloads. Thus, the effect of the pressure conditions is limited. In contrast, broadband random vibration loads and high-frequency acceleration loads during launch can cause changes in the optical alignment and small structural deformations. These effects can lead to focal plane shift and image quality degradation [19]. Nevertheless, few studies have reported quantitative test results for launch vibration environments from the viewpoint of the functional performance of optical systems, particularly focus retention.

Loss of focus and contrast in biological images can affect not only visual clarity but also the reliability of later quantitative analysis. In cell imaging, the focus condition and image acquisition settings can change the intensity gradient at cell boundaries and the accuracy of segmentation. Unclear boundaries can lead to underestimation or overestimation of the cell region. If incorrectly segmented cells are included in the analysis, measurements of cell area, shape, and fluorescence intensity may be biased. It may also become more difficult to detect biologically meaningful morphological changes caused by treatment conditions. Therefore, the retention of optical contrast and edge sharpness after the launch environment should be evaluated to ensure reliable data from microscope-based space

life science missions [20]. Dima et al. reported that segmentation accuracy changes with image conditions that determine cell boundary sharpness. Hill et al. showed that poor segmentation can reduce the ability to detect morphological changes [21].

For spaceborne optical payloads, changes in the optical alignment and the need for focus correction after launch and on-orbit environments have been repeatedly reported. Thiel et al. [22] obtained live cell fluorescence microscopy images under microgravity by using a FLUMIAS microscope mounted on a TEXUS-54 suborbital rocket. They reported that in-flight measurements started approximately 66 s after launch, and focus plane correction was required before the actual measurement because focus shifted owing to launch vibration and acceleration. In the field of space telescopes, several studies have verified the changes in optical performance caused by the launch and on-orbit environments. Rohrbach et al. [23] measured the major alignment parameters of the Integrated Science Instrument Module of the James Webb Space Telescope, including the focus, pupil shear, pupil clocking, and boresight, through cryogenic vacuum tests. They also performed launch-level vibration and acoustic tests to simulate the possible performance changes caused by launches. Hartig et al. [24] recorded significant coma and defocusing in the initial observations of the Advanced Camera for Surveys of the Hubble Space Telescope, and demonstrated that these aberrations can be improved through optical alignment correction using real-time commands. This is an example in which focus correction is required in an actual orbit. Kaneda et al. [25] reported that near-infrared star images obtained during the initial on-orbit observations by the AKARI infrared space telescope were significantly blurred. Based on model and image analyses, they moved the secondary mirror twice along the optical axis to correct the focus. These previous studies show that the verification of focus retention performance is essential for spaceborne optical payloads intended for high-resolution imaging.

Studies on laminated passive vibration isolation technologies have been conducted to reduce vibrations in spaceborne payloads. Park et al. [26] proposed a three-axis passive launch vibration isolation system that combined superelastic shape memory alloy blades with multilayered viscous lamina, and verified the possibility of reducing the dynamic loads transmitted to a small satellite through static load and launch vibration tests. Kwon et al. [27] also proposed a blade-type passive vibration isolator composed of a viscoelastic acrylic tape and multilayered metal plates, and demonstrated its capability to reduce microvibrations generated by a spaceborne cryocooler. These studies show that a laminated structure composed of viscoelastic and structural layers can effectively dissipate the vibration energy in spaceborne payloads. In particular, optical instrument-based payloads can suffer performance degradation even under small vibration disturbances [28]. Therefore, vibration isolation is essential to ensure the image quality [29].

Previous studies have reported changes in optical alignment and the need for focus correction after launch and in on-orbit environments. They have also reported the dynamic response reduction performance of vibration isolators for space payloads. However, experimental studies that quantify focus retention of a COTS microscope module using image contrast changes before and after launch-environment tests are limited. Studies that compare the vibration response and optical function of isolated and non-isolated configurations are also limited. Therefore, this study used two COTS microscope units of the same model. One unit was assigned to the isolated configuration, and the other was assigned to the non-isolated configuration. Focus retention was evaluated using the focus retention ratio (FRR) before and after the random vibration and shock tests.

2. Overview of Microscope Module

2.1. Microscope Module Configurations

In this study, a cylindrical microscope was selected for the vibration test. The camera used to acquire images of the observation target had dimensions of 18.4 mm × 38 mm × 38 mm and a mass of 15 g. A Raspberry Pi High Quality Camera (Raspberry Pi Ltd., Cambridge, UK) equipped with a 12.3 megapixel Sony IMX477 image sensor (Sony Semiconductor Solutions Corporation, Atsugi, Kanagawa, Japan) was used. The diagonal dimensions of the sensor is 7.9 mm. Figure 1 shows the configuration of the microscope and camera, and Table 1 summarizes the specifications of the microscope. This study used two COTS microscope units of the same model. One unit was assigned to the non-isolated configuration, and the other was assigned to the isolated configuration. The same microscope and camera models and the same image acquisition conditions were used for both units. The mounting condition was defined by whether the vibration isolator was applied.

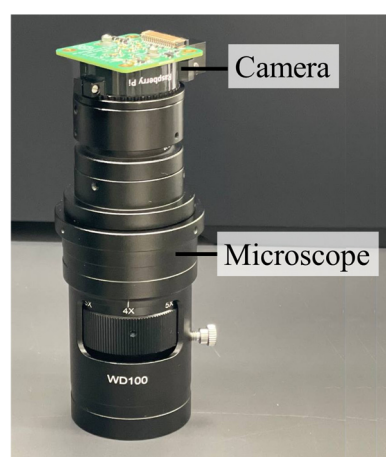


Figure 1. Commercial optical microscope module used in this study.

Table 1. Specifications of the COTS optical microscope module.

Specification	Value
Type	C-mount industrial zoom microscope
Working distance (mm)	100
Magnification range	0.7×–5.0×
Dimensions (D × L)	55 mm × 150 mm
Weight (g)	485

The microscope module consists of a clamping bracket, base bracket, displacement prevention bracket, and either a rigid bracket or vibration isolator, as shown in Figure 2. Because the COTS microscope does not have an interface for direct mechanical fastening to a space structure, it was fixed using a clamping method that surrounded the outer surface of the microscope. Delrin was applied to the clamping bracket to prevent microslip and damage that may occur owing to direct metal-to-metal contact. The clamping bracket was connected to the structure using an aluminum-based bracket.

A Delrin displacement prevention bracket was installed under the base bracket to support the lower surface of the microscope. This bracket was designed to limit the relative displacement of the microscope that may occur along the axial direction in launch vibration environments. In this study, two configurations were compared to evaluate the optical performance degradation caused by the launch vibrations. For the configuration without vibration isolation, a rigid aluminum bracket was installed under the base bracket to realize

a rigid connection. In the configuration with vibration isolation, a passive vibration isolator was installed under the base bracket.

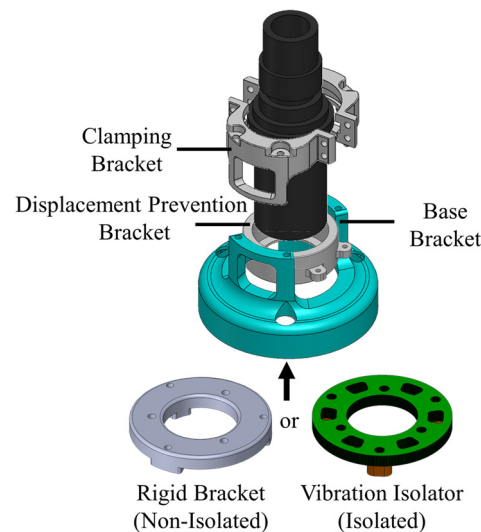


Figure 2. Microscope module configuration: rigidly mounted non-isolated configuration and vibration-isolated configuration.

2.2. Vibration Isolator

In this study, a laminated blade-type vibration isolator based on viscoelastic tape was designed for multiaxis vibration control. This isolator was selected based on its performance as verified in previous studies. Figure 3 shows the overall configuration and a cross-sectional view of the vibration isolator. The isolator consists of laminated blades and interface brackets that connect the blades to the structure.

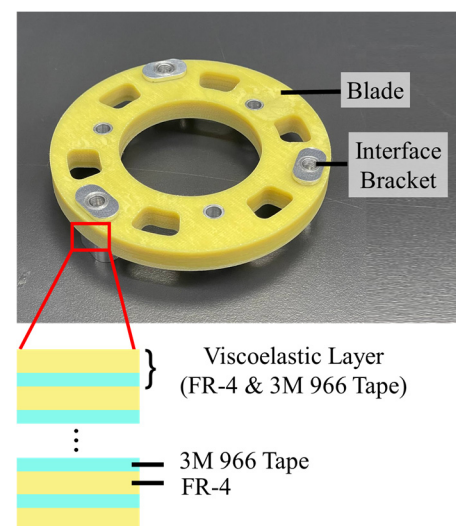


Figure 3. Laminated passive vibration isolator: overall configuration and cross-sectional arrangement of the FR-4 constraining layers and 3M 966 viscoelastic tape layers.

The laminated blade consisted of an alternating stack of thin FR-4 plates (3M Center, St. Paul, MN, USA) and 30 layers of 3M™ Adhesive Transfer Tape 966 (3M Company, St. Paul, MN, USA). The FR-4 plates exhibited a relatively high elastic modulus and acted as constraining layers to provide shear stiffness. The viscoelastic tape was placed between the two constraining layers and acted as a damping layer that induced shear deformation.

When bending deformation occurs in the blade owing to the launch vibration, a relative displacement is generated between the adjacent layers in the laminated structure.

Consequently, shear deformation is concentrated in the viscoelastic tape layers. During shear deformation, a viscoelastic material converts mechanical energy into thermal energy through an internal loss factor, leading to the damped structural response. Each viscoelastic tape layer has a thickness of approximately 0.1 mm, enabling a compact and lightweight laminated structure. The multilayered stack of thin constraining and viscoelastic layers increases the energy dissipation and provides passive high-damping vibration isolation characteristics. Table 2 summarizes the main properties of the 3M 966 viscoelastic tape used in this study [30].

Table 2. Properties of 3M 966 viscoelastic tape [30].

Specification	Value
Type	Acrylic adhesive transfer tape
Thickness (mm)	0.06
Adhesion strength to steel (N/100 mm)	58 (20 min Dwell)
	85 (72 h Dwell)
	159 (Ultimate Bond)
Allowable temperature (°C)	−40 to 232

2.3. Observation Target

A USAF 1951 Resolution Test Chart was used as the observation target to quantitatively evaluate image quality degradation of the microscope after the vibration test. This chart is an optical resolution test pattern defined by the U.S. Air Force standard MIL-STD-150A in 1951. It is used to evaluate the spatial resolution of the imaging systems based on regular bar patterns. It has been widely used to verify the performances of microscope- and camera-based optical systems [31].

The overall USAF 1951 target (Figure 4) is approximately 0.7 mm × 0.5 mm. The focus retention performance was calculated using the average brightness difference between the black and white bars in the vertical pattern region of Group 6. After comparing the contrast of several candidate elements in the reference image, an element with a spatial frequency lower than that of the finest element that could be stably resolved was selected as the reference region.

The line contrast in the selected region was defined using the Michelson contrast and was calculated using Equation (1).

$$C = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

(1)

where $I_{\max}$ is the average brightness of the bright bars in the selected pattern region, and $I_{\min}$ is the average brightness of the dark bars.

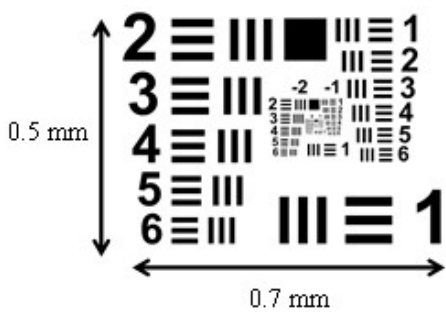


Figure 4. USAF 1951 resolution test target used for the image-based focus retention assessment.

The focus retention performance was evaluated by comparing the image acquired before the vibration test with the image acquired after the vibration test. In this study, the focus retention ratio (FRR) was defined to quantitatively compare the change in line contrast before and after the vibration test. The FRR is the line contrast after the vibration test normalized by the line contrast before the vibration test, as given in Equation (2).

$$\text{FRR} = \frac{C_{\text{after}}}{C_{\text{before}}} \quad (2)$$

where C_{before} and C_{after} are the line contrasts calculated from the images before and after the vibration test, respectively. An FRR value close to one indicates that the focus condition was maintained after the vibration test, whereas an FRR value close to zero indicates that the line contrast of the reference pattern is degraded, which implies that the image quality is reduced. In this study, $\text{FRR} = 0.8$ was used as a study-specific engineering screening threshold for comparing the relative focus retention performance of the two mounting configurations, rather than as a general internal acceptance criterion. This value means that at least 80% of the pre-test line contrast is retained after the test, or that the relative reduction in line contrast is limited to 20%. NASA CR-132457 presents a design case in which a 20% reduction in MTF due to tracking-error-induced image smear was allocated in the performance budget of a specific imaging system. This case does not use the same metric as FRR and is not a standardized acceptance criterion. It was used only as an engineering reference for limiting contrast-transfer performance loss caused by a specific degradation factor [32].

3. Launch Environment Verification Test

3.1. Launch Vibration Test

Launch vibration tests were performed for the two microscope module configurations described in Section 2.1 to evaluate the structural response and focus retention performance. For the Z-axis test, the test article was mounted on the shaker through the base test jig. For the x- and y-axis tests, a dedicated fixture was used to rotate the test article. The same mounting fixture and fastening conditions were used for the random vibration and LLSS tests in each direction. The revised Figure 5 shows the x-, y-, and z-axis test setups and the test article coordinate system. Before the microscope module was installed, a fixture-only LLSS was performed at 2 g over 20–2000 Hz. No clear fixture resonance that could dominate the test article response was observed in the frequency range of interest. Vibration responses were measured using a Dytran Instruments Model 3023A triaxial IEPE accelerometer. No additional recalibration or traceability verification was performed immediately before the test. The nominal sensitivity of the sensor is 10 mV/g, and the measurement range of each axis is ± 500 g. According to the manufacturer's specifications, the frequency response is within $\pm 5\%$ from 1.5 to 4000 Hz. The broadband resolution is approximately 0.007 grms, and the maximum transverse sensitivity is 6%. The sensor mass is approximately 3 g, and the sensor was adhesively mounted on the clamping bracket. This frequency response range covers the LLSS and 20–2000 Hz random vibration measurement ranges used in this study. The x-, y-, and z-axis markings on the sensor housing were aligned with the specimen coordinate system and the machined reference surfaces of the test fixture. The corresponding measurement axis was placed parallel to the shaker direction for each test.

Random vibration tests were performed in the order of -6 , -3 , and 0 dB to verify whether the optical performance of the microscope could be maintained under the random vibration environment generated during the launch. The vibration specifications followed NASA Standard 7000B; the detailed specifications are summarized in Table 3 [33]. The random vibration tests for each microscope unit were performed sequentially in the order

of z - x - y . Therefore, the images and FRR values measured after the z -axis test reflect the z -axis loading history. The results measured after the x -axis test include the preceding z - and x -axis loading histories. The results measured after the final y -axis test include the full z - x - y test sequence. Therefore, the results at each stage were not interpreted as independent single-axis results. They were evaluated as cumulative focus-retention results after the sequential multi-axis tests.

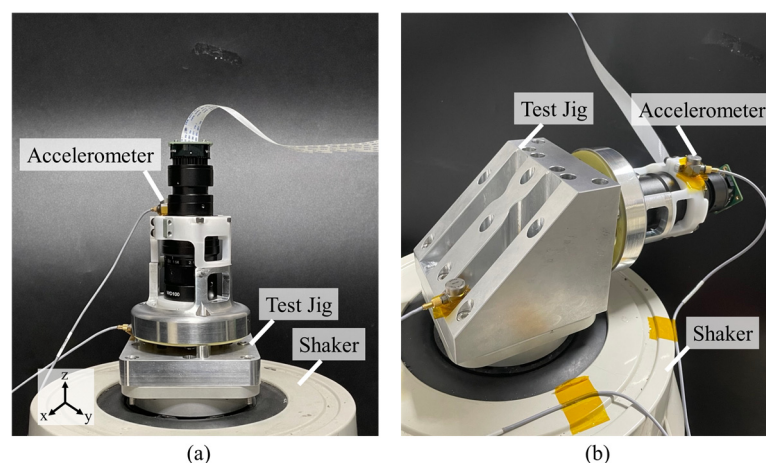


Figure 5. Test setup for the vibration tests: (a) z -axis configuration, and (b) x - and y -axis configuration. The microscope module, test jig, accelerometer, and shaker are indicated.

Table 3. Random vibration test standard [33].

Parameter	Specification	
Direction	x, y, z -axis	
Duration (min/axis)	2	
Profile	Frequency (Hz)	PSD Acceleration (g^2/Hz)
	20	0.0260
	50	0.1600
	800	0.1600
	2000	0.0260
	Overall (g_{rms})	14.1

In addition, LLSS tests were performed before and after each test level to check for structural abnormalities during the test. The main natural frequency changes before and after the test were compared with the 5% criterion [34]. The occurrence of damage caused by vibration loading was evaluated by comparing the changes in the natural frequency and transfer characteristics obtained from the LLSS tests. The conditions for the LLSS test are presented in Table 4.

Table 4. Low-level sine sweep test condition.

Parameter	Specification	
Direction	x, y, z -axis	
Type	Harmonic	
Sweep Rate	2 oct/min	
Profile	Frequency (Hz)	Amplitude (g)
	20	0.2
	2000	0.2

Figure 6a–c show the random vibration test results along each axis for the configurations with and without the vibration isolator. For the configuration without the vibration isolator, the acceleration-response PSDs along the x - and y -axis directions exhibited similar trends with overall acceleration responses of 10.87 and 10.47 g_{rms} , respectively. In contrast, the z -axis response was 18.81 g_{rms} , which was approximately 1.7 times higher than those in the x - and y -axis directions. This result was caused by the difference in acceleration transmissibility because the support stiffness in the z -axis direction was higher than those in the x - and y -axis directions.

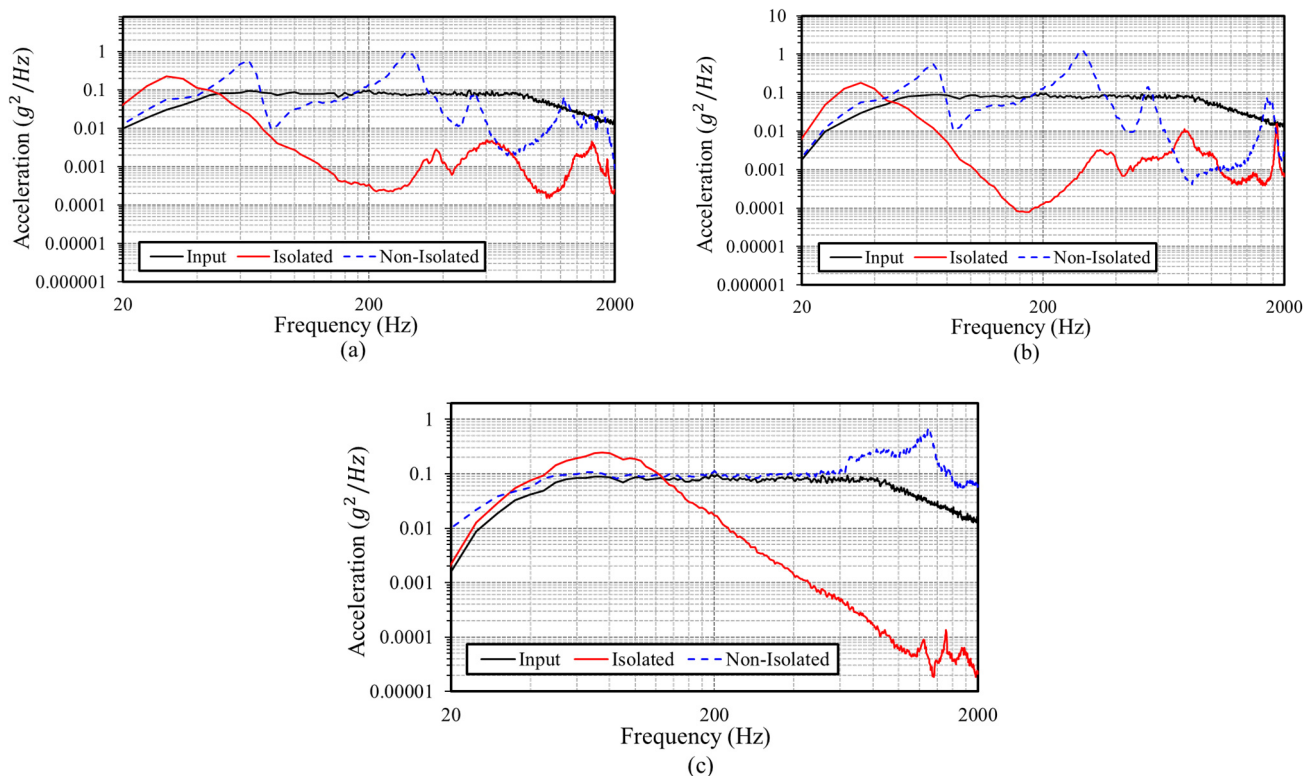


Figure 6. Acceleration power spectral density responses measured during the random vibration tests for the isolated and non-isolated configurations: (a) x -axis, (b) y -axis, and (c) z -axis responses. The shaker input PSD is also shown for comparison.

For the configuration with the vibration isolator, the overall responses in the x - and y -axis directions were 2.75 and 2.78 g_{rms} , respectively. The z -axis response was 4.75 g_{rms} . This corresponds to an approximately threefold reduction in the response compared to the configuration without the vibration isolator. In particular, the z -axis response was reduced by approximately 3.96 times.

This reduction in the response was caused by the laminated blade structure of the vibration isolator. When bending deformation occurs, shear deformation is concentrated in the viscoelastic layers. During this process, the vibration energy is dissipated by the internal loss factor of the viscoelastic material. Consequently, the equivalent damping ratio of the system increases, and the response amplification in the resonance region is suppressed. Therefore, as the vibration level increases, a larger shear deformation can occur and the response reduction effect may become more pronounced. Figure 7 presents a comparison of the overall responses for each configuration along each axis. The equivalent damping ratios of the isolated configuration were estimated by applying the half-power bandwidth method to the LLSS acceleration transmissibility curves. The acceleration transmissibility,

$T(f)$, was calculated by dividing the response acceleration measured on the microscope module, $a_{\text{response}}(f)$, by the shaker input acceleration, $a_{\text{input}}(f)$.

$$T(f) = \frac{a_{\text{response}}(f)}{a_{\text{input}}(f)} \quad (3)$$

For each axis, the maximum transmissibility, T_{max} , and the corresponding resonance frequency, f_r , were identified. The lower and upper half-power frequencies, f_1 and f_2 , were defined at $T_{\text{max}}/\sqrt{2}$. Linear interpolation was used to determine the crossing frequencies between adjacent measurement points.

$$T_{\text{HP}} = \frac{T_{\text{max}}}{\sqrt{2}} \quad (4)$$

$$f_{\text{HP}} = f_a + \frac{T_{\text{HP}} - T_a}{T_b - T_a}(f_b - f_a) \quad (5)$$

The equivalent damping ratio was calculated as follows.

$$\zeta_{\text{eq}} = \frac{f_2 - f_1}{2f_r} \quad (6)$$

The estimated equivalent damping ratios were 0.19, 0.23, and 0.61 in the x -, y -, and z -axis directions, respectively. The corresponding (f_1, f_r, f_2) values were (25.37, 31.14, 36.91) Hz for the x -axis, (21.94, 29.03, 35.41) Hz for the y -axis, and (20.90, 82.41, 120.93) Hz for the z -axis. Because the system contains a laminated viscoelastic structure and has broad resonance regions, these values were treated as equivalent bandwidth-based damping estimates rather than rigorous modal damping ratios of individual modes.

For the configuration without the vibration isolator, the first mode was observed at approximately 70 Hz in the x - and y -axis directions, and at approximately 650 Hz in the z -axis direction. For the configuration with the vibration isolator, the natural frequencies were 30, 35, and 78 Hz along the x -, y -, and z -axis, respectively. This indicates that the first natural frequency of the overall system shifts to a lower frequency range owing to the reduction in stiffness caused by the vibration isolator. The overall response to the random input vibration was effectively reduced because the resonance frequency shifted to a lower frequency range and the damping increased simultaneously.

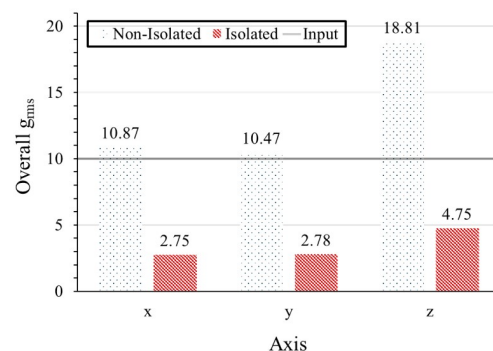


Figure 7. Comparison of the overall acceleration responses measured for the isolated and non-isolated configurations during the x -, y -, and z -axis random vibration tests.

Table 5 summarizes the LLSS test results obtained before and after the vibration tests for each configuration. The maximum change in the natural frequency before and after the test was 3.56%. This satisfies the commonly used structural integrity criterion of less than 5%. Therefore, the structural integrity of the microscope module was confirmed under the

vibration test conditions. In addition, a visual inspection after the test showed no damage to the external structure of the microscope or vibration isolator.

Table 5. Comparison of the natural frequencies measured before and after the vibration tests for the isolated and non-isolated configurations.

Case	Axis	Pre-Test (Hz)	Post-Test (Hz)	Difference (%)
Non-Isolated	<i>x</i>	66.95	66.73	0.32
	<i>y</i>	36.69	36.26	1.17
	<i>z</i>	656.5	660.3	0.5
Isolated	<i>x</i>	31.14	32.25	3.56
	<i>y</i>	28.35	28.68	1.16
	<i>z</i>	83.38	83.38	0.00

3.2. Shock Test

Figure 8 shows the shock test setup for the microscope module. The shock was generated using a pendulum hammer. The microscope module was mounted on the shock test machine using a dedicated test jig. A hammer mass of 12 kg, a release angle of 40 degrees, the impact location, and the test article mounting conditions were kept constant for all tests. An accelerometer was attached to the clamping bracket to measure the acceleration response under shock loading. The shock test was performed along the three axes of the microscope. For each axis, the test was repeated three times under the same conditions to evaluate the repeatability of the shock transmission characteristics.

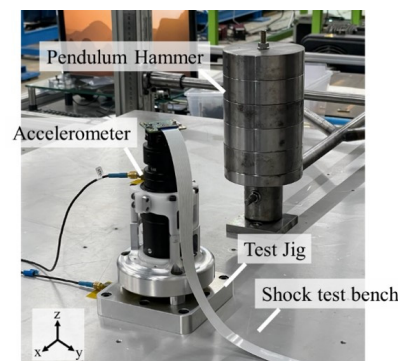


Figure 8. Pendulum–hammer shock test setup for the microscope module, showing the pendulum hammer, test jig, accelerometer, and shock test bench.

In this test, an SRS (Shock Response Spectrum) input condition with a maximum acceleration of 20 g was applied. The maximum SRS response along each axis is calculated based on the measured acceleration response. Figure 9 shows the shock test results for the three axes of the microscope. The change in the SRS response caused by the vibration isolator varies depending on the axis and frequency range. In some frequency ranges, the response tended to decrease after isolator incorporation. However, the difference was not significant in the main response range, and similar response levels were maintained in the specific frequency ranges.

This result indicates that the proposed vibration isolator can reduce the response to vibration inputs with a relatively long duration owing to the damping effect of the viscoelastic layers. However, its energy dissipation effect is limited to shock inputs with short durations and broad frequency components. Although the change in response owing to the vibration isolator was not significant, visual inspection confirmed that the structural integrity of the microscope module was maintained.

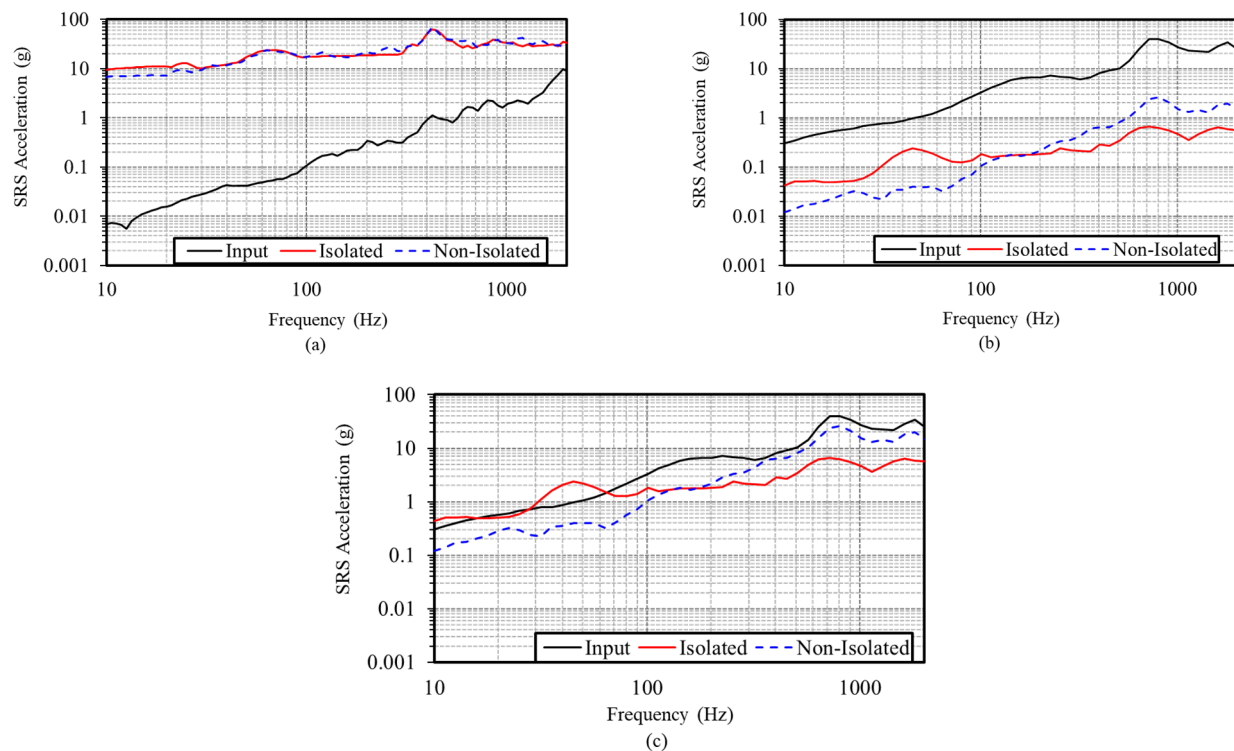


Figure 9. Shock response spectra measured for the isolated and non-isolated configurations: (a) x -axis, (b) y -axis, and (c) z -axis responses. The applied input SRS is also shown for comparison.

3.3. Results of Launch Environment Verification Test

The focus-retention results of the microscope showed a different trend from the structural-state assessment based on the pre- and post-test LLSS. Table 6 shows the USAF 1951 images acquired before and after the random vibration tests performed in the order of z - x - y for each microscope unit. The result after the z -axis test reflects only the z -axis load. The result after the x -axis test includes the preceding z - x loading sequence. The result after the y -axis test includes the cumulative effect of the full z - x - y test sequence. The focus retention states of the configurations with and without a vibration isolator were visually compared.

In the configuration without the vibration isolator, the line sharpness of the USAF 1951 target gradually degraded as the test sequence progressed. After the z -axis test, no significant change in focus was observed compared to the image before the test. However, after the x -axis test, the line boundaries became blurred and the contrast decreased, whereas, the resolution of the target lines degraded significantly after the final y -axis test. For the configuration with the vibration isolator, image sharpness was maintained at a level similar to that before the test.

Figure 10 shows the FRR values calculated by analyzing the line contrast of the USAF 1951 target images acquired after each axis test stage. This analysis was performed to evaluate the focus shift trend observed in Table 6 quantitatively.

For the configuration without the vibration isolator, the FRR was maintained at 0.91 after the z -axis test, satisfying the criterion. However, after the sequential z - x tests, the FRR decreases to 0.47, which does not satisfy this criterion. After the full z - x - y test sequence, the FRR decreased further to 0.06. This result agrees with the image comparison presented in Table 6. For the configuration with the vibration isolator, after the z -, x -, and y -axis tests, the FRR remained at approximately 0.91–0.92, satisfying the focus retention criterion.

Table 6. USAF 1951 target images and focus retention ratios measured before testing, after the z-axis test, after the sequential z-x tests, and after the full z-x-y random vibration test sequence for the isolated and non-isolated configurations.

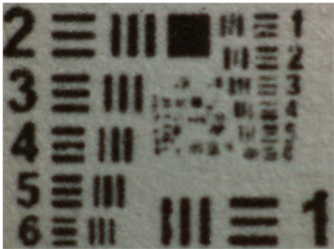
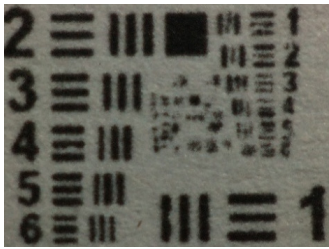
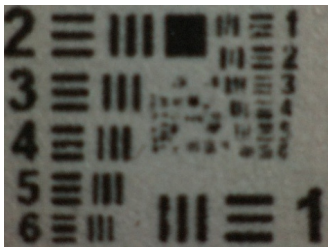
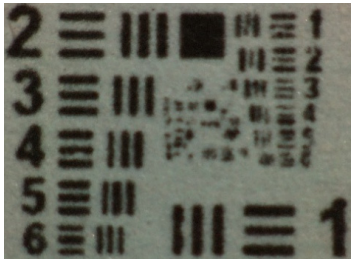
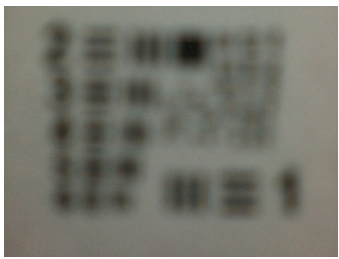
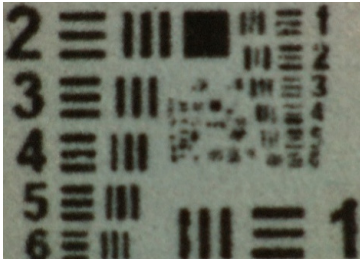
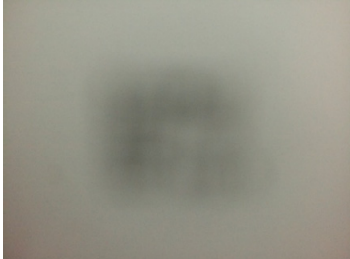
Test	Isolated	Non-Isolated
Before Test		
After z-axis	 FRR = 0.92	 FRR = 0.91
After sequential z-x tests	 FRR = 0.91	 FRR = 0.47
After sequential z-x-y tests	 FRR = 0.92	 FRR = 0.06

Table 7 summarizes images of the USAF 1951 target acquired using a microscope before and after the shock test. For each configuration, the images acquired before and after the z-, x-, and y-axis shock tests are presented. The focus retention states of the configurations with and without a vibration isolator were visually compared.

Line sharpness and contrast were maintained in the images acquired after the shock test, and no focus deviation was observed.

The quantitative evaluation showed that the contrast ratios after all shock tests were 0.87 and 0.86 for the configurations with and without the vibration isolator, respectively. Both configurations satisfied the focus retention criterion of 0.8. Unlike the gradual contrast degradation and image sharpness reduction observed in the random vibration test, image quality was maintained after the single-event shock loads.

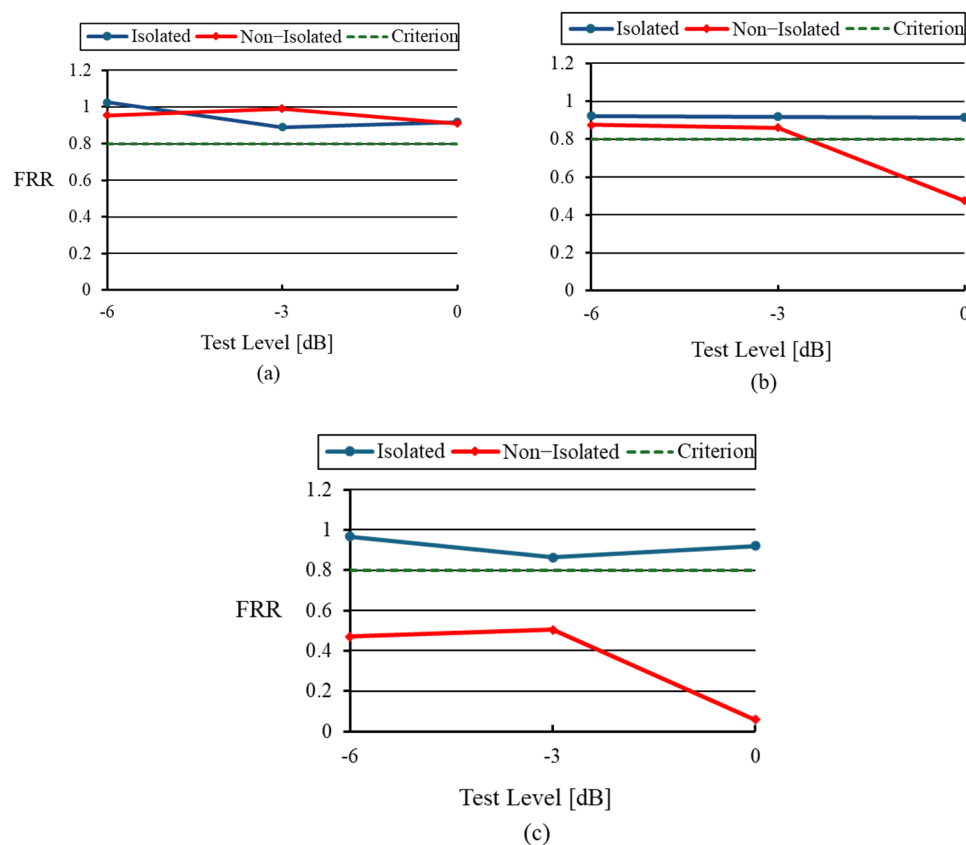


Figure 10. FRR measured after each stage of the sequential random vibration test for the isolated and non-isolated configurations: (a) after the z-axis test, (b) after the sequential z-x tests, and (c) after the full z-x-y test sequence. The study-specific screening threshold of FRR = 0.8 is also indicated.

Table 7. USAF 1951 target images and focus retention ratios measured before testing and after each stage of the sequential z-, x-, and y-axis shock tests for the isolated and non-isolated configurations.

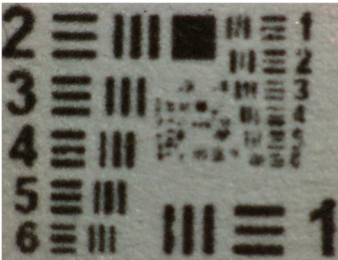
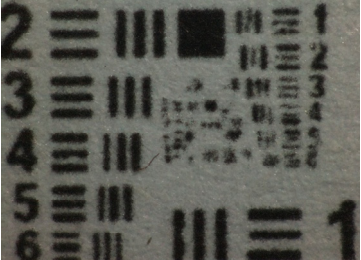
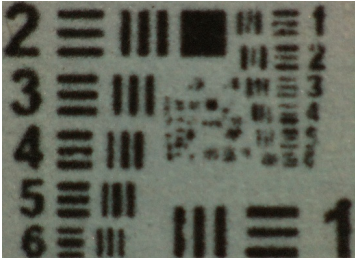
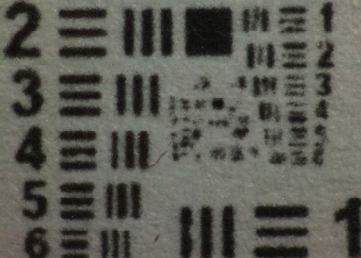
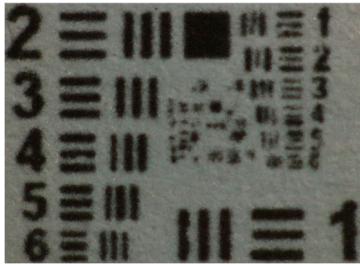
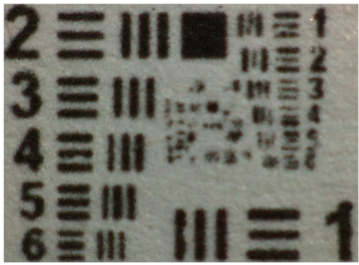
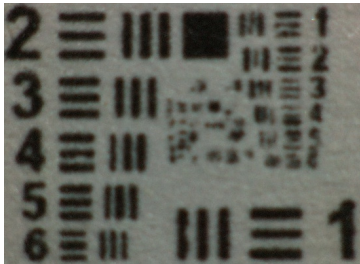
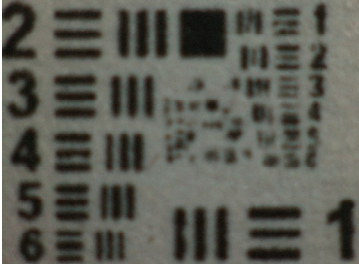
Test	Isolated	Non-Isolated
Before Test		
After z-axis		
	FRR = 0.91	FRR = 0.92

Table 7. Cont.

Test	Isolated	Non-Isolated
After sequential z-x tests		
	FRR = 0.92	FRR = 0.93
After sequential z-x-y tests		
	FRR = 0.87	FRR = 0.86

4. Discussion

For the COTS microscope units and mounting configurations tested in this study, the retention of global structural characteristics and the retention of optical function showed different trends. The maximum change in the main natural frequencies identified by the pre- and post-test LLSS was 3.56%. Visual inspection also showed no visible damage to the microscope module or the vibration isolator. Therefore, no clear change in the measured global structural characteristics was observed under the applied test conditions. However, the non-isolated unit showed a large decrease in line contrast and FRR after the random vibration test. For the tested microscope units and mounting conditions, this result indicates that structural assessment based on LLSS and visual inspection may not fully identify small functional changes in internal optical alignment or focus related assemblies. Therefore, image-based functional assessment should be used as an additional procedure to complement the verification of payloads that are sensitive to optical performance.

The focus retention results also support this interpretation. In the non-isolated configuration, the highest overall acceleration response was measured during the z-axis test. However, the FRR remained at approximately 0.91 after the z-axis test. In contrast, the FRR decreased to 0.47 after the sequential z-x-axis tests and further decreased to 0.06 after the full z-x-y-axis test sequence. Therefore, the focus degradation observed in this test was not simply proportional to the magnitude of the overall acceleration response. Possible causes include the relative sensitivity of the internal lens or magnification adjustment assembly to lateral loading, the cumulative loading history from the preceding axis tests, or a combination of both factors.

The difference between the configurations with and without the vibration isolator demonstrates the effectiveness of the laminated passive vibration isolator in maintaining the focus stability. The configuration without the vibration isolator exhibited relatively high acceleration responses, particularly along the optical axis direction. In contrast, the configuration with the vibration isolator reduced the overall acceleration response by up to 3.96 times. This reduction can be attributed to the combined effects of stiffness reduction and energy dissipation in the laminated viscoelastic structure. The insertion of the vibration

isolator shifts the dominant natural frequencies to a lower frequency range and increases the equivalent damping of the system through shear deformation in the viscoelastic layers. Consequently, resonance amplification was suppressed, and the vibration transmitted to the microscope module was reduced. The reduced vibration response was associated with retention of the pre-test focus condition in the isolated configuration after the random vibration test.

A comparison between the random vibration and shock test results indicated that the broadband random vibration was more critical than shock loading for the tested microscope module. In the configuration without the vibration isolator, the line contrast of the USAF 1951 target gradually degrades as the axis-wise random vibration tests progress. This trend suggests that repeated broadband excitations may induce cumulative effects on the internal focus-related components of the microscope, such as microslips, slight loosening, or positional changes in the magnification adjustment assembly. By contrast, the shock test did not cause significant focus degradation in either configuration. The FRR values for both configurations satisfied the focus retention criterion. Although the shock input contained broad frequency components, its short duration did not produce the same cumulative effect as that observed during random vibration loading.

These findings have practical implications for the verification of COTS optical instruments used in space biomedical applications. COTS microscope modules are attractive for space payloads because they can reduce development costs and schedules. However, they are generally designed for ground operations and may include internal focus or magnification adjustment mechanisms that are sensitive to launch vibrations. Therefore, qualifications based only on structural survivability can overlook functional degradation, which directly affects the image-based scientific data. For microscope-based biomedical observation payloads, the image quality is directly related to the reliability of the acquired biological data. Therefore, image-based functional verification, such as FRR assessment using a resolution target, should be included in the launch environment verification.

The present study has several limitations. First, two COTS microscope units of the same model were used, but only one independent test unit was used for each mounting configuration. Therefore, unit-to-unit variations caused by manufacturing tolerances, internal lens alignment, and the assembly condition of the focus or magnification mechanism could not be statistically separated. The results should therefore be interpreted as comparative observations for the two tested units under the applied mounting and test conditions. Second, FRR was based on the line contrast measured in a selected local ROI on the USAF 1951 target. This method provides a consistent comparison of local focus-retention performance before and after the test, but it does not represent full-field optical performance. Therefore, spatially nonuniform optical degradation, such as lens tilt, sensor-to-optical axis misalignment, field curvature, asymmetric aberrations, and peripheral defocus, may not be fully identified by the present evaluation. Third, the FRR threshold of 0.8 was not directly derived from the science requirements or optical performance requirements of a specific space mission. Therefore, meeting this threshold does not directly mean that the microscope retains sufficient performance for all biological observation tasks. For an actual mission, a mission-specific acceptance threshold should be established based on the minimum feature size of the observation target, the required spatial resolution, the spatial frequency range of interest, the imaging method, and the intended image-analysis task.

Future studies should address these limitations through repeated tests using different microscope units and through the development of a detailed viscoelastic finite element model. The model should independently predict the natural frequencies, damping characteristics, and random vibration responses and should be compared with the experimental results.

5. Conclusions

In this study, the focus stability of two nominally identical COTS optical microscope units for space biomedical payload applications was experimentally evaluated under launch vibration and shock environments. A laminated viscoelastic passive vibration isolator was incorporated into one microscope unit, and its performance was comparatively assessed using one microscope unit for each of the isolated and non-isolated configurations. Global structural characteristics were evaluated using LLSS results and visual inspection, whereas functional stability was evaluated using FRR analysis based on USAF 1951 resolution target images.

The random vibration test showed that the isolated configuration reduced the overall acceleration response by up to 3.96 times compared with the non-isolated configuration. The LLSS results and visual inspection showed no significant change in the measured global structural characteristics or visible damage after the vibration test. However, the non-isolated configuration exhibited clear focus degradation after the random vibration test. In contrast, the isolated configuration maintained an FRR above the study-specific engineering screening threshold of 0.8. The shock test results showed that no marked focal degradation was observed for either configuration. The FRR values after the shock test were 0.87 and 0.86 for the isolated and non-isolated configurations, respectively, both remaining above the study-specific FRR screening threshold. These results indicate that broadband random vibration produced greater focus degradation than short-duration shock loading under the applied test conditions.

The main contribution of this study is the experimental demonstration of the value of image-based functional verification for COTS optical instruments intended for space biomedical payload applications. The results showed that conventional structural assessments alone did not fully indicate optical performance retention for the tested microscope units and mounting configurations. Therefore, launch-environment verification of microscope modules for space biomedical observation should complement structural assessments with focus-retention and image-quality evaluations. The FRR-based assessment approach and laminated passive vibration isolation concept provide a practical basis for evaluating compact optical payloads for future space biomedical and microgravity research. Because one independent microscope unit was used for each mounting configuration, the observed differences should be interpreted as comparative results for the two tested units rather than as statistically generalized performance characteristics of the entire microscope model. In addition, the FRR threshold of 0.8 was used as a study-specific engineering screening value rather than a mission-derived acceptance criterion. Mission-specific thresholds should be established based on the minimum observable feature size, required spatial resolution, and intended image analysis task.

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Conflicts of Interest: Authors Yeon-Hyeok Park and Hyun-Ung Oh were employed by the company STEPLab. Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

COTS	commercial off-the-shelf
FRR	focus retention ratio
PSD	power spectral density
LLSS	low-level sine sweep
SRS	shock response spectrum

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