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Vibration test of upper stage engine for KSLV-II

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Abstract
An upper stage engine is mounted on a launch vehicle and is exposed to severe dynamic loads during flight. The dynamic loads are generated by the combustion of the first stage engines until the upper stage separation. Therefore, it is crucial to ensure the structural integrity of the upper stage engine against these dynamic loads prior to the actual flight test. In this regard, the vibration test is one of the important tasks in the upper stage engine development process and its qualification test. This paper presents the overall process of the vibration test conducted on the upper stage engine for KSLV-II.

1. Introduction

1.1 Vibration environment

A launch vehicle consists of two or more stages to enhance launch efficiency. During the combustion of the first stage engines, upper stage engines are mounted on the launch vehicle and considered as a payload, similar to satellites. In this configuration, the upper stage engines experience significant dynamic loads during the flight. The upper stage engines must operate perfectly even after being exposed to the dynamic loads for the success of the entire launch mission.
The dynamic loads on the upper stage engine are classified as transportation, wind, lift-off, and maneuvering loads during the flight of the launch vehicle [1]. Each dynamic load is associated with specific frequency range and can be simulated using the shaker. The objective of the vibration test on the upper stage engine is to simulate the dynamic loading conditions as closely as possible to the actual flight environment. As a part of the engine development process, the vibration tests have already been conducted on other upper stage engines to verify its structural integrity against the dynamic loads [2-4].

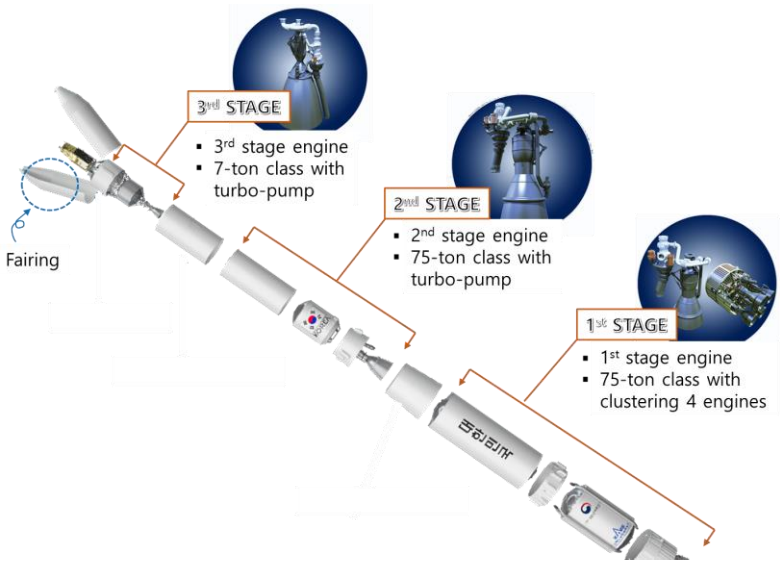

Figure 1: Engine configuration of Korea Space Launch Vehicle-II

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Figure 1 shows the configuration of the Korea Space Launch Vehicle-II (KSLV-II). The KSLV-II is a three stage launch vehicle, and it is necessary to conduct the vibration tests on the upper stage engines and ensure their normal operation and performance before the actual flight test of KSLV-II. This paper aims to provide an overview of the vibration test conducted on the third stage engine of KSLV-II. The third stage engine is a 7-ton class liquid propellant rocket engine, and the ground hot-firing test was successfully completed [5]. As a part of the engine qualification test, the vibration test is considered during the engine development process.

1.2 Test procedure

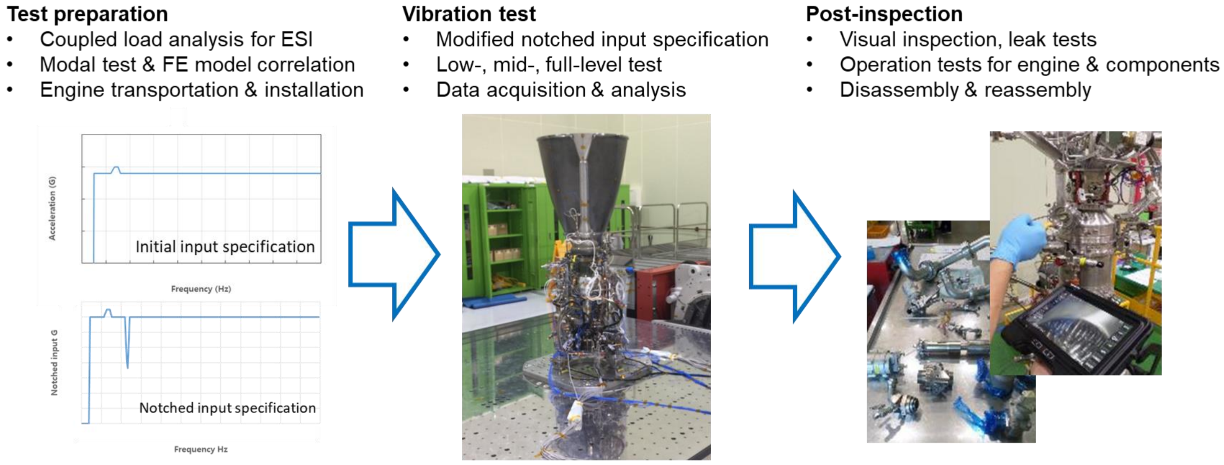

Figure 2: Vibration test procedure for upper stage engine

Figure 2 shows the vibration test procedure for the upper stage engine. The vibration test consists of three main stages: test preparation, vibration test, and post-inspection. The test engine is prepared to have the same configuration with the actual flight engine. During the engine assembly process, modal tests and finite element (FE) model correlation are conducted on the test engine and its corresponding FE model. To determine the sine input specification for the vibration test, coupled load analysis (CLA) is performed on the full-scale KSLV-II model. The notched input specification is then derived from the sine input specification based on the FE analysis results of the maximum force and moment at the engine interface. The vibration test is conducted using the notched input specification. Subsequent to the vibration test, leak and functional tests are performed on the test engine and its components. The test engine is disassembled for the functional test and internal inspection of each component after the engine level post-inspection. Once the components have been disassembled and post-inspected, all the components are reassembled. As the final step of the engine qualification process, the hot-firing test is conducted using the reassembled engine. By conducting the vibration test and post-inspection, the structural integrity of the engine against the dynamic loads is verified prior to the actual flight test.

2. Test preparation

To conduct a thorough vibration test on the upper stage engine, several preparatory tasks must be completed beforehand. These test preparations allow for obtaining useful information, conducting appropriate tests, and achieving the objective of the vibration test. Rocket engines, in particular, pose challenges due to their relatively heavy weight, large size, and complex assembly of numerous components. Therefore, the proper test preparation is crucial for the vibration test including the engine transportation and installation process. This chapter provides an overview of the preparation tasks for vibration test.

2.1 Modal test & FE model correlation

Prior to the main vibration test, modal tests and FE model correlation were conducted using the test engine and its corresponding FE model. The correlated FE model, obtained from the modal test, can be used for various purposes. It assists in determining the appropriate levels of the sine input specification for the vibration test and provides useful information for the overall process of the vibration test.

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The test engine was assembled to have the same configuration with the actual flight model. During the engine assembly process, the modal test was conducted starting from a single-component level and progressing to the sub-assembled and fully-assembled level. The initial FE model was then updated using the modal test results to match the dynamic characteristics between the test results and analysis results, including natural frequencies, mode shapes, and damping of the test engine. Figure 3 shows the correlation results between the modal test and FE model using the fully-assembled engine. The modal assurance criterion (MAC) results demonstrated a high level of accuracy by updating the model test results to the FE model.

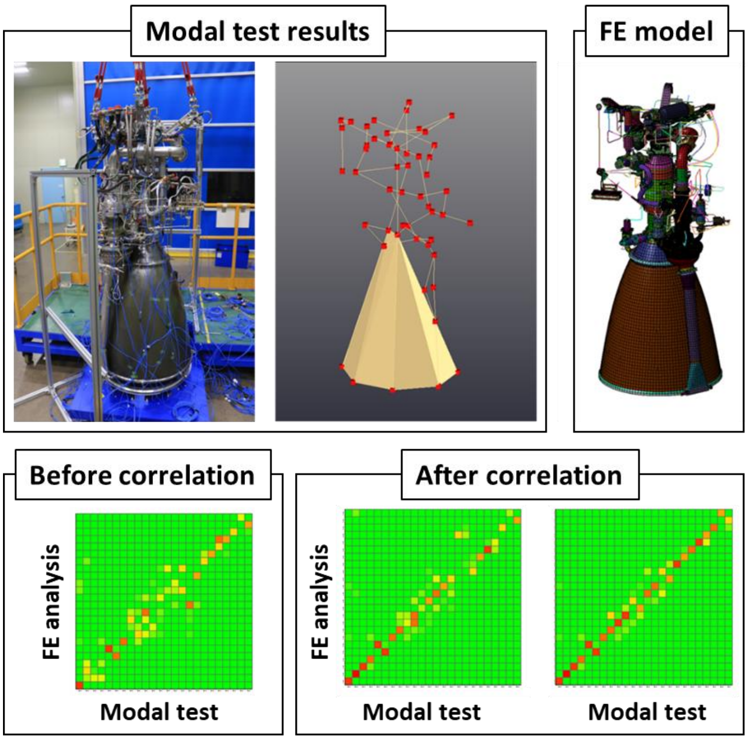

Figure 3: Modal test and FE model correlation with modal assurance criterion

2.2 Initial notched input specification

To archive the objective of the vibration test for the upper stage engine, it is crucial to define test input loads that accurately simulate the dynamic loads transmitted to the engine during the flight of the launch vehicle. The test input specification was derived from the CLA results of the full-scale KSLV-II model, incorporating its test flight data. However, the direct application of the test input specification to the vibration test is not feasible due to significant differences in engine interface boundary conditions between the actual launch vehicle and vibration test setup. Therefore, the sine input specification from the CLA results should be appropriately adjusted to prevent overload during the vibration test caused by the differences in boundary conditions.

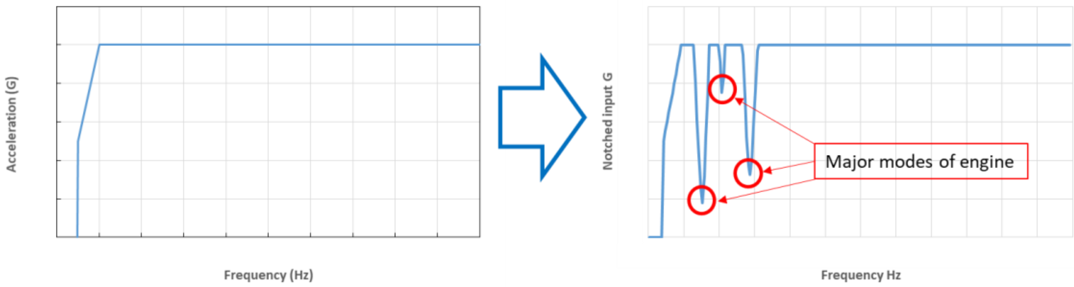

Figure 4: Initial notched input specification for vibration test

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To obtain the appropriate test input specification, the frequency response function (FRF) analysis was conducted using the correlated FE model. The force and moment on the engine interface within the test frequency range were calculated from the FRF analysis. The analysis results of the maximum force and moment under the different interface conditions of the test engine were compared, and the initial notched input specification was generated. Figure 4 shows the comparison results of the sine input specification between the CLA model and vibration test setup. Specific frequency ranges associated with particular major engine modes were adjusted to lower levels to prevent the overload on the engine during the vibration test.

2.3 Test preparation

Several preparatory tasks were completed prior to the vibration test, including the design and evaluation of the test fixtures, jigs, and transportation/installation devices. The test fixture, which connects the shaker table or expander head with the engine interface, was designed to minimize its dynamic effect on the vibration test results. The first mode natural frequency of the text fixture was set significantly higher than the target frequency of the sine input specification. Additionally, the interface bolts, which may experience concentrated loads during the vibration test, were designed with sufficient safety margins to ensure the safety of the engine under the test conditions. Figure 5 shows the modal analysis results of the test fixture during its design process. The natural frequency of the test fixture and the safety margins of the interface bolts were checked beforehand to verify their suitability for the vibration test.

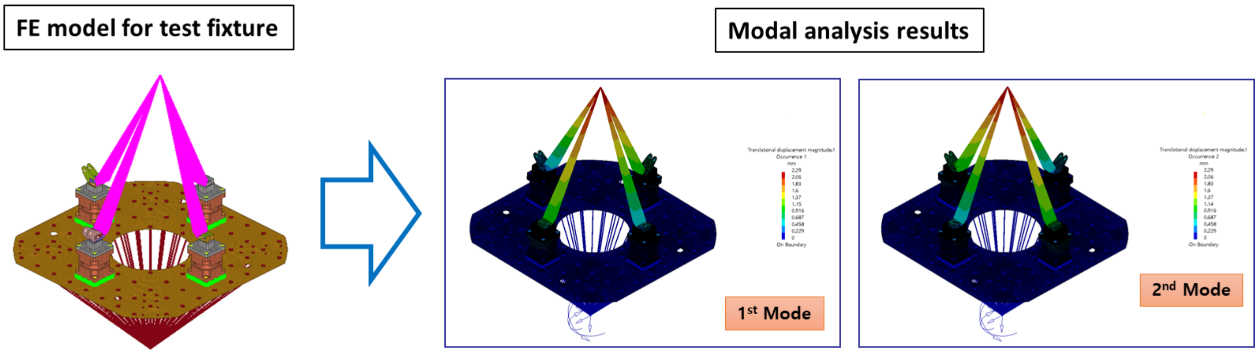

Figure 5: Modal analysis results of test fixture

Next, a method for the engine transportation and installation fixture was established for the vibration test. Careful handling is necessary during the transportation and installation. Typically, engines are assembled and stored with the nozzle outlet facing downward. However, for the vibration test, the nozzle outlet must be oriented upward, and the upper interface section of the engine is placed on top of the shaker. In this case, it is necessary to determine a safe and secure approach to transport and reverse the test engine for the vibration test. Once the test engine is successfully installed on the shaker, all fixtures and jigs should be entirely removed from the test engine to proceed the vibration test.

2.4 Sensor installation

Various types of sensors are utilized to monitor and evaluate the conditions of the test engine during and after the vibration test. These sensors provide useful data that enables the analysis of the dynamic characteristics, control of the input levels, and evaluation of the safety margins for the test engine and its major components throughout the vibration test. Multiple accelerometers, strain gauges, and load cells were installed at the critical points of the test engine. The installation locations of these sensors were determined based on the results of the modal test and FE analysis, which effectively represent the major behavior of the test engine.
For the vibration test, a total of 60 three-axis accelerometers were installed. 5 accelerometers were attached to the base plate of the shaker to monitor the excitation level from the sine input specification. The remaining 55 accelerometers were installed on the test engine. Several accelerometers on the test engine were utilized to derive and control the sine input specification during the vibration test. Figure 6 shows an example of the accelerometer placement on several components of the test engine. The installation locations of the accelerometers were determined based on the results of the modal test and FRF analysis, where the major dynamic characteristics of the test engine are effectively represented.

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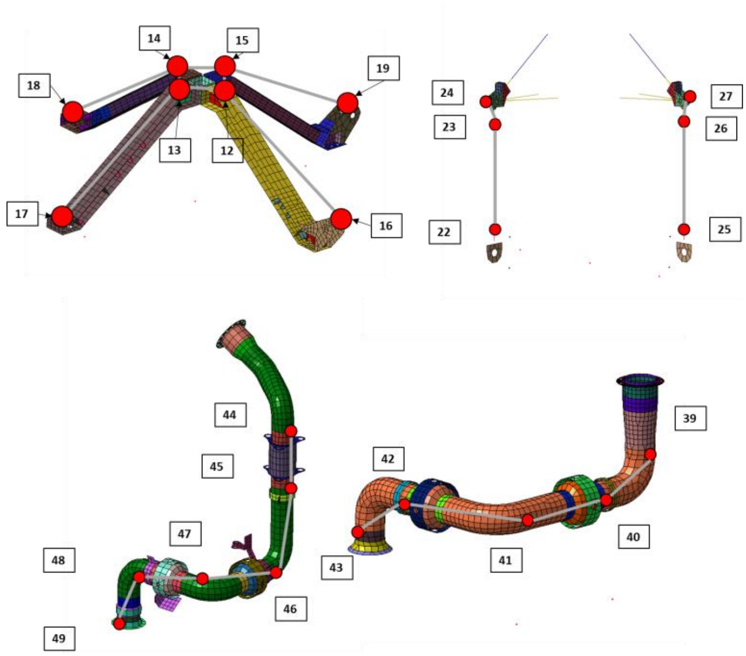

Figure 6: Accelerometer placement on engine components

Figure 7 shows the reduced wireframe model used for the test geometry. Each point of the reduced wireframe model represented the placement of installed accelerometers with an identical local axis orientation for each accelerometer. After the vibration test, the measured data from all accelerometers were updated to each point of the reduced wireframe model, and the behavior of the engine during the vibration test can be easily identified through the reduced wireframe model.

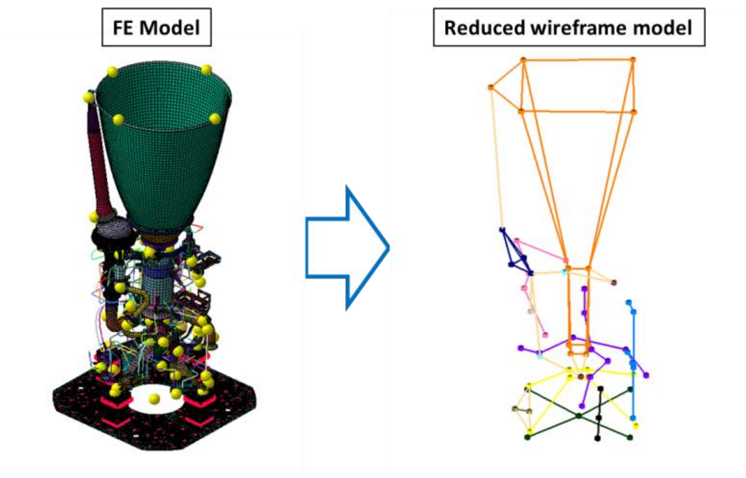

Figure 7: Reduced wireframe model of test engine

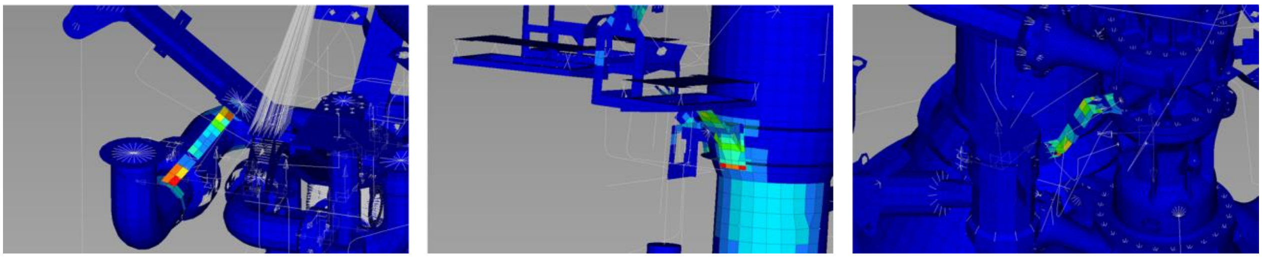

Figure 8: Stress analysis results of test engine for strain gauge installation

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For the vibration test, a total of 7 rosette strain gauges were installed. The strain gauges were attached at the critical points of the test engine to evaluate the safety margin under the dynamic loading conditions. The installation location of the strain gauges was selected based on the stress analysis results of the test engine as shown in Figure 8. The margin of safety (MOS) was then calculated using the measurement results obtained from the strain gauges.
Furthermore, three-axis load cells were installed to measure the transmitted loads at the engine interface sections. A total of 4 load cells were installed between the shaker table and engine truss to accurately measure the forces acting on the engine interface during the vibration test.

3. Vibration test

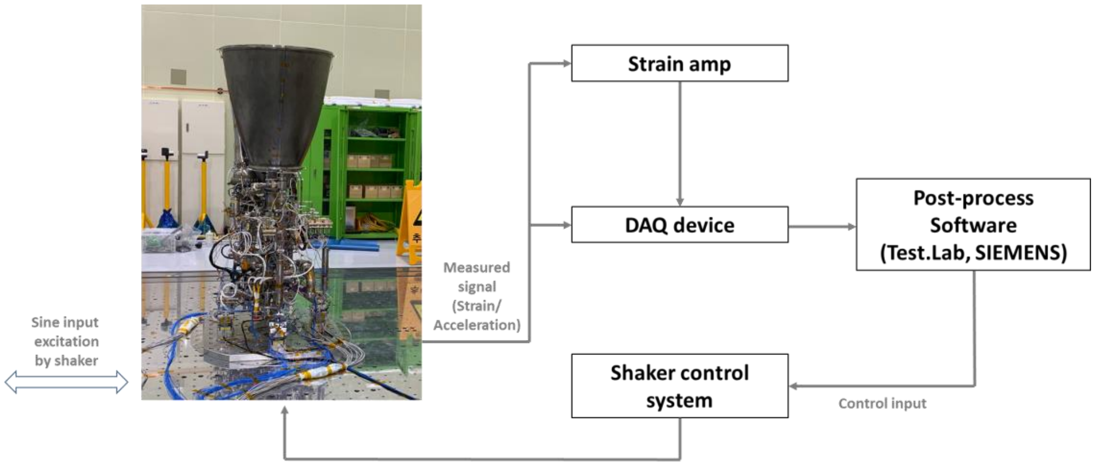

Figure 9: Configuration of vibration test

Figure 9 shows the configuration of the vibration test. The test engine was securely mounted on the shaker table including the installed sensors and cables. The measured signals were conditioned using amplifiers and recorded by data acquisition (DAQ) equipment. The acquisition and post-processing of the measured data were carried out using Test.Lab, a commercial software by SIEMENS.
Table 1 shows the overall process of the vibration test. The vibration test consisted of three test levels: low-, mid-, and full-level test. The mid- and full-level vibration tests were conducted using the notched input specification for each axis of x, y, and z with a sine sweep.

Table 1: Overall process of vibration test for upper stage engine

Test	Excitation level	Objective
Pre-test	0.05G	Obtaining reference database
25% mid-level test	25% of full-level	Modifying input specification
Low-level test	0.05G	Comparing characteristics change
50% mid-level test	50% of full-level	Modifying input specification
Low-level test	0.05G	Comparing characteristics change
75% mid-level test	75% of full-level	Modifying input specification
Low-level test	0.05G	Comparing characteristics change
Full-level test	Full-level	Full-level vibration test
Low-level test	0.05G	Comparing characteristics change

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3.1 Pre-test

A Pre-test is conducted on the test engine before the main vibration test, applying a low level of 0.05 G. The low-level of the pre-test is not expected to cause structural damage to the test engine. The objective of the pre-test is to obtain the dynamic characteristics of the full-scale engine system. Figure 10 shows the FRF results of the test engine, measured during the pre-test. The FRF results revealed the presence of several natural frequencies corresponding to particular mode shapes, including torsional, bending, shear, and oval modes of the test engine. As shown in figure 10, the FRF results of the test engine exhibited distinct mode shapes associated with particular natural frequencies. If any structural damages occur on the test engine after the vibration test, the dynamic characteristics would change under the same excitation level. Therefore, by comparing these changes in dynamic characteristics before and after the vibration test, it is possible to evaluate the condition of the test engine under the dynamic loads.

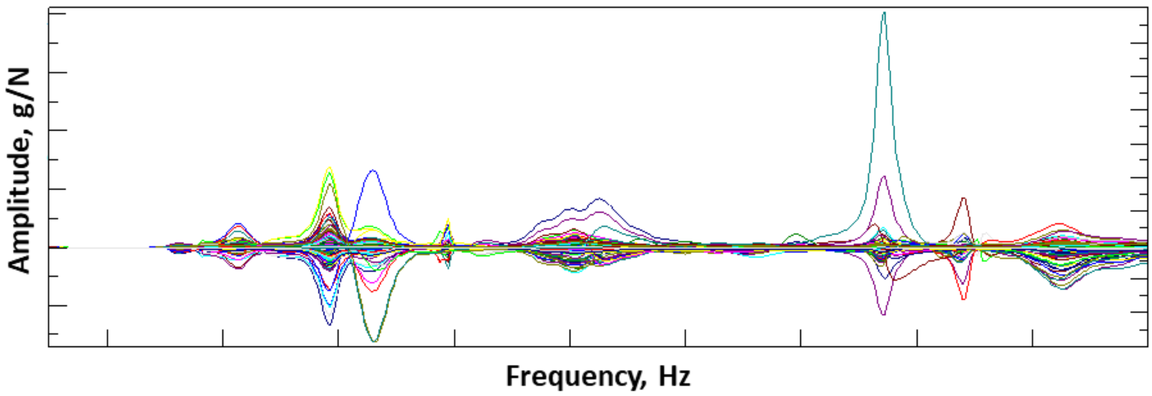

Figure 10: Frequency response function of test engine during pre-test

The dynamic characteristics obtained from the pre-test were utilized to update the correlated FE model of the test engine. The updated FE model was then used to modify the initial notched input specification for the mid-level test. Figure 11 shows the comparison result of the notched input specification after the adjustment. Based on the results of the pre-test, the central frequency of the first bending mode was shifted to a lower frequency range.

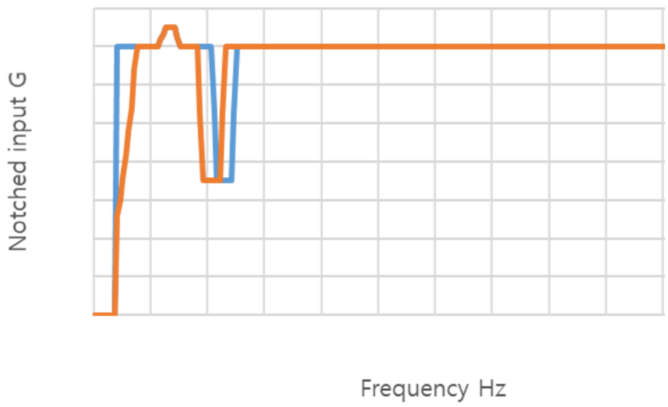

Figure 11: Adjustment of notched input specification based on pre-test

3.2 Mid-level test

After modifying the notched input specification based on the pre-test results, the mid-level test was conducted at various steps, including 25%, 50%, and 75% of the full-level test. The objective of the mid-level test is as follows. The engine allows movement of the nozzle direction for thrust vector control (TVC). To allow the movement of the engine nozzle, several components have degrees of freedom against the engine gimbal motion, such as bearings, bellows, and hinge structures. Additionally, several pipe supports enable sliding movement of the pipe to absorb thermal deformation during the engine operation. These movable components exhibit non-linear characteristics under different

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levels of excitation loads [6]. Due to the non-linear characteristics of these components, the notched input specification from the pre-test cannot be directly applied to the full-level test. Therefore, the notched input specification from the pre-test should be modified, considering the nonlinearity of the engine system caused by its movable components. The changes in the dynamic characteristics of the test engine at different excitation levels were examined by gradually increasing the input level from 25% to 75%. Figure 12 shows the FRF results of the test engine at different excitation levels. The natural frequencies of several modes were shifted with increasing excitation level.

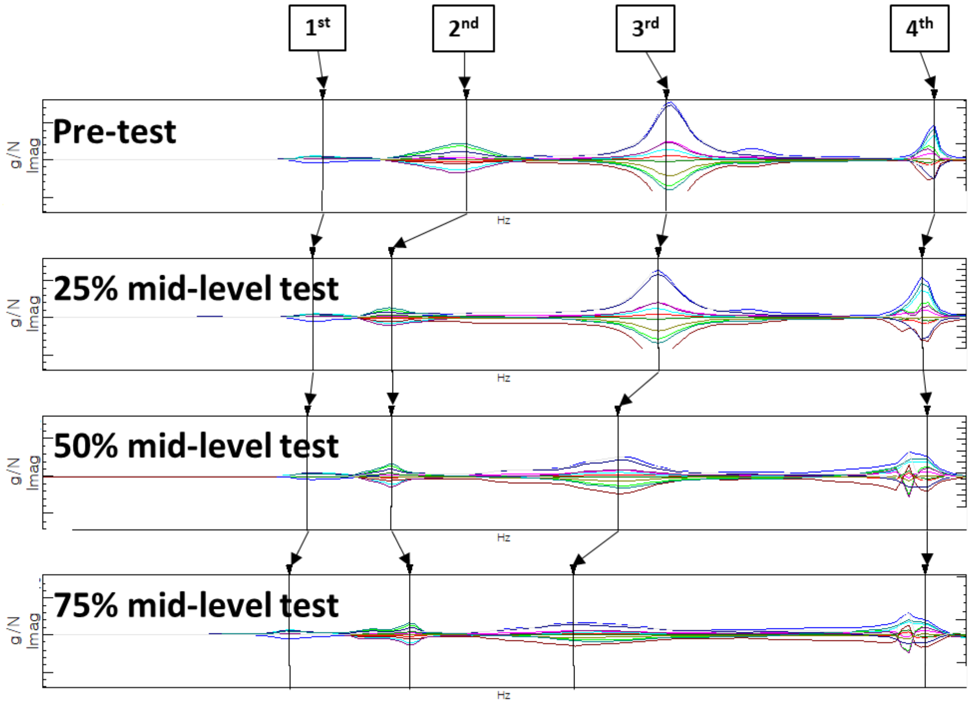

Figure 12: FRF results of test engine at different excitation level

The notched input specification for each middle-level test was estimated based on the results of the previous mid-level test. For example, the notched input specification for the 50% mid-level test was estimated and modified from the results of the 25% mid-level test. This iterative process allowed for fine-tuning the notched input specification as the excitation level increased.
Similarly, the notched input specification for the full-level test was estimated based on the changing tendency in the dynamic characteristics of the test engine observed during the mid-level tests. Figure 13 shows the comparison of notched input specification from the results of the FE model analysis and 75% mid-level test. The notched input specification for the full-level test was estimated by considering the nonlinearity of the test engine.

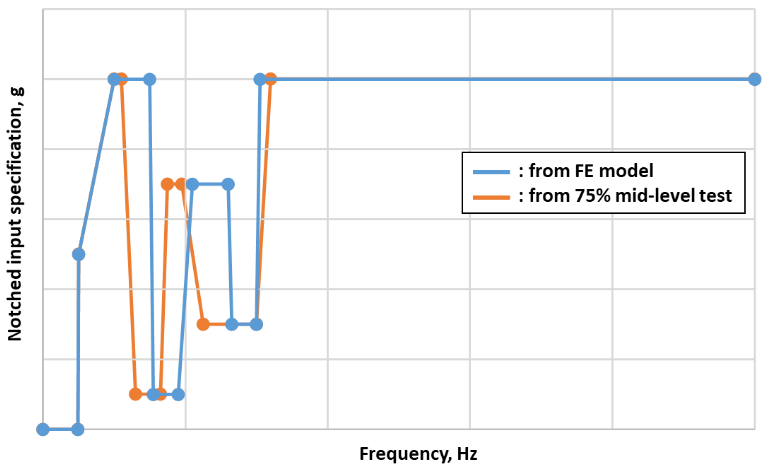

Figure 13: Comparison of the notched input specification

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3.3 Full-level test

After the completion of the mid-level test, the full-level test was conducted using the modified input specification. To compare the dynamic characteristics of the test engine before and after the full-level test, the low-level test was also conducted. Figure 14 shows the comparison of the FRF results at the low-level excitation before and after the mid- and full-level tests. The comparison results revealed that the FRF results before and after the vibration test exhibited a similar trend within the target frequency range. However, differences in the magnitude of the response were identified at specific frequencies in several modes, which were results from the non-linearity of the engine components, particularly in modes associated with movable components. In case where frequency differences occurred, the magnitude of the response was significantly lower than the other major modes. In conclusion, the FRF comparison results remained consistent before and after the full-level test, suggesting that the test engine maintained its dynamic characteristics throughout the vibration test.

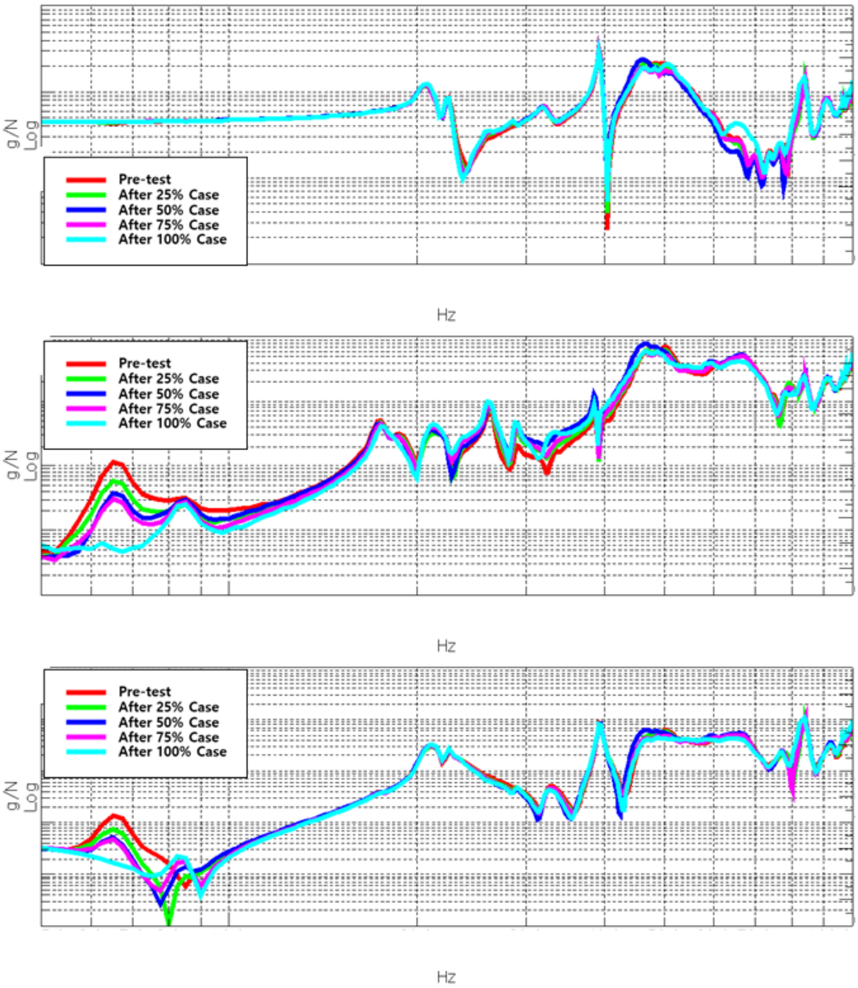

Figure 14: Comparison of FRF at low-level excitation after mid- and full-level test

The strain data measured from the full-level test was converted into the equivalent stress to evaluate the margin of safety (MOS). Von-Mises stresses were calculated based on the measurement results of the rosette strain gauges. Figure 15 shows the strain measurement results during the full-level test. The high strain levels were measured at the specific modes of the test engine, including the overall torsional, bending, shear, and several local modes of its components. All strain measurement results showed the allowable stress level during the full-level test.
Based on the analysis results of the full-level test, it was confirmed that the test engine had no problems after being exposed to the dynamic loads. No significant changes in the dynamic characteristics of the entire engine system were observed after the full-level test, and the major structures of the test engine showed the sufficient safety margin. The analysis results of the measurement data indicated that no significant changes of the structural behavior were observed from the test engine after the full-level test.

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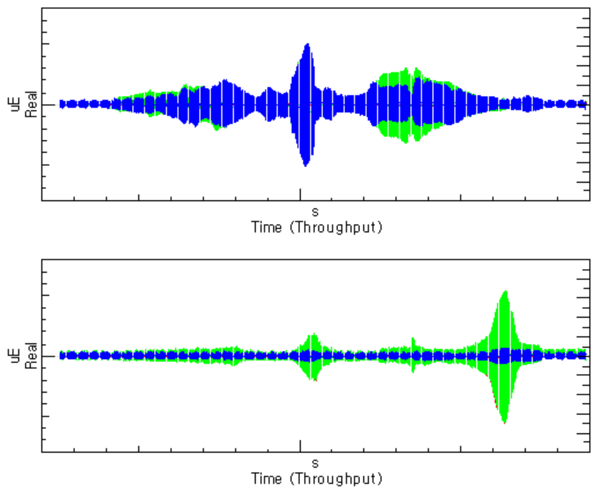

Figure 15: Strain measurement results during full-level test

3.4 Post-inspection and qualification test

After the completion of the full-level test, several post-inspections were conducted to verify the normal operation of the engine and its components. The post-inspections included the external visual inspection, leak tests, sensor signal checks, and component operation tests. Additionally, the functional test of the engine system, which is regularly performed prior to the normal engine combustion test, was conducted to assess the condition of the engine after the vibration test. Following the post-inspection process, the test engine was disassembled to inspect several components that are particularly vulnerable to the dynamic loads.
Through this series of the post-inspections and tests, it was confirmed that the test engine and all components exhibited no problems in terms of function and performance after being exposed to the dynamic loads.
Finally, the disassembled components were reassembled onto the full-scale engine, and the combustion test was conducted using the reassembled engine as the final qualification test. The combustion tests were successfully carried out without any problems using the vibration-tested and reassembled engine. The results of vibration test and post-inspection demonstrated that the developed engine met all the qualification requirements after undergoing the vibration test.

4. Summary

The vibration test was considered during the development process of the upper stage engine to verify its structural integrity against the dynamic loads experienced during the flight of KSLV-II. The newly developed upper stage engine underwent rigorous tests with the dynamic loads, and met all the qualification requirements without any structural and functional problems after the vibration test. Following the successful development and qualification of the upper stage engine, it was delivered to KSLV-II program. From 2021 to 2023, the KSLV-II was launched three times, with the last two missions achieving success.
Throughout the vibration test, various testing techniques, including test preparations, test methods, and analysis methods, were established and applied. These techniques have provided valuable insights and data for the development of the upper stage engine. Furthermore, it is expected that these testing techniques will continue to be utilized in future development projects for next-generation launch vehicles in Republic of Korea, contributing to the advancement of space exploration and technology.

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