Combustion Stability Improvement of LE-9 Engine for Booster Stage of H3 Launch Vehicle

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The Space System Division of Mitsubishi Heavy Industries, Ltd. (MHI) is currently developing a new flagship launch vehicle (H3) in cooperation with the Japan Aerospace Exploration Agency (JAXA). As a test for the development of the LE-9 first stage engine for the H3 launch vehicle, a full-scale combustion system test was implemented. Through improvement in the injector and resonator by establishing and applying a proprietary combustion stability evaluation tool, significant improvement in combustion stability was attained. Currently an actual engine is being designed and fabricated based on the test results, and a combustion test of the total engine systems is planned to be implemented in 2017.

1. Introduction

MHI is currently developing the H3 launch vehicle in order to reduce cost and improve reliability in comparison with the current H-2A/B launch vehicle. In the development of a launch vehicle, the launch vehicle engine is one of the important factors that affect the reliability, cost and performance. As the first stage engine of the H3 launch vehicle, the new LE-9 engine is currently under development. A launch vehicle engine generates propulsive power by increasing the propellant pressure through the use of a turbo pump (rotating machine), injecting the boosted propellant into the combustion chamber through the injector to burn it under a high-temperature and high-pressure condition, and using the heat energy generated by the combustion to accelerate the flow in the nozzle to supersonic speed. **Figure 1** shows schematic views of the injector and the combustion chamber structure. Because the combustion temperature of hydrogen and oxygen exceeds 3000°C, cooling is provided through the use of cryogenic hydrogen flowing inside the wall of the combustion chamber. The internal surface of the combustion chamber is made of a thin wall with a thickness of several millimeters in order to enhance the cooling efficiency. If the combustion is unstable, the pressure vibration is amplified and the quantity of heat transferred to the wall increases to the level where the cooling capacity of the combustion chamber becomes insufficient, resulting in the erosion of the combustion chamber. Because the erosion of the combustion chamber is a serious phenomenon that leads directly to engine breakdown, it is essential for the development of a launch vehicle engine to secure sufficient combustion stability.

The components that are important for securing combustion stability are the injector and resonator. The injector injects hydrogen and oxygen through hundreds of injecting elements in order to prevent the local high heat load of the combustion chamber. The resonator, which is located between the injector and the combustion chamber, suppresses the pressure fluctuation through resonance phenomena in a space. This paper reports on the improvement in combustion stability of the LE-9 engine brought about by changing the shape of the injecting element and the resonator.

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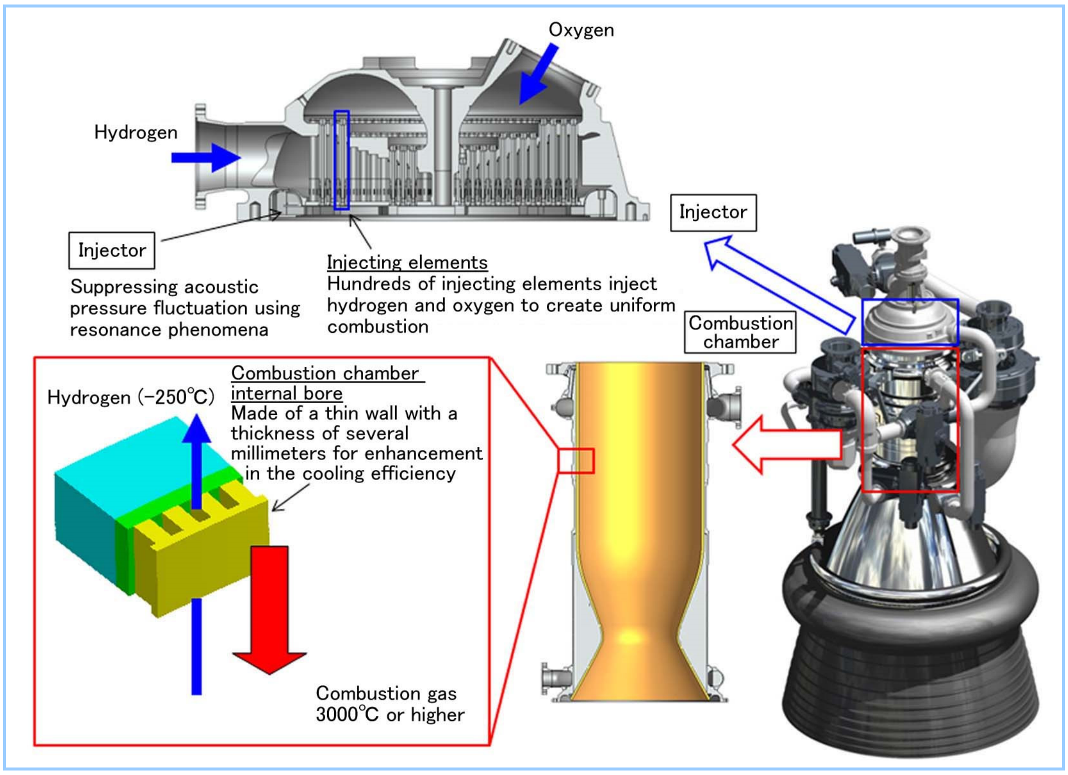

Figure 1 Structure of injector and combustion chamber

2. LE-9 engine

Table 1 compares the specifications of the LE-9 engine with existing engines. The LE-9 engine adopts an expander bleed cycle similar to the LE-5B engine. **Figure 2** compares the expander bleed cycle and the two-stage combustion cycle. The expander bleed cycle uses part of the hydrogen boosted by the turbo pump for the cooling of the combustion chamber and utilizes the heat energy acquired at that time to drive the turbo pump. Then, hydrogen with its pressure decreased when driving the turbo pump enters into the nozzle, and flows along the adjacent of the wall surface while cooling it (film cooling). On the other hand, the two-stage combustion cycle uses all the hydrogen for the cooling of the combustion chamber and the nozzle, then burns it in the sub combustion chamber together with part of the oxygen, and drives the turbo pump through the heat energy generated by the combustion. Because all the propellant is burnt in the main combustion chamber, the performance is higher than that of the expander cycle. However, the number of parts is increased due to the existence of the sub combustion chamber and the system is complicated, resulting in difficult engine control, and therefore this cycle is disadvantageous for cost reduction and reliability improvement. For that reason, we adopted for the LE-9 engine an expander cycle similar to the LE-5B engine, aiming at an increase in the propulsive power of the expander cycle utilizing the design technologies for the single-stage high-pressure engine that we cultivated in the past.

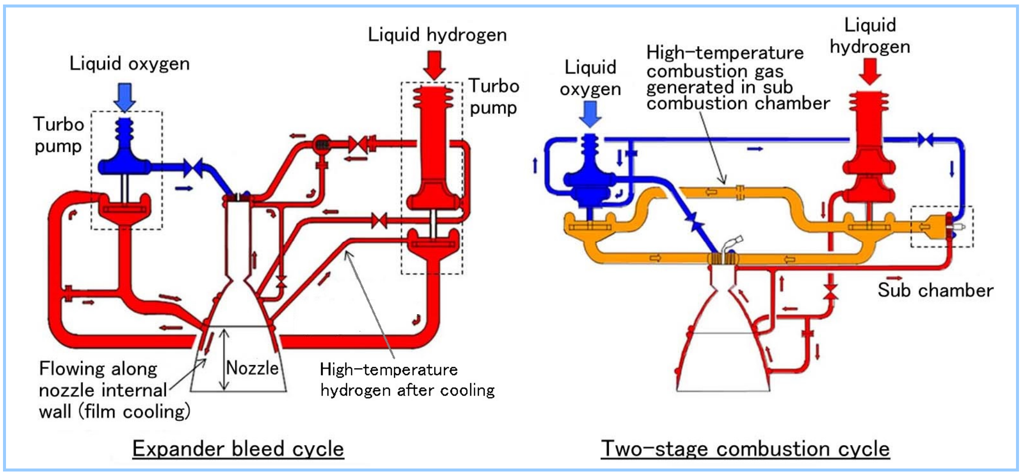

Figure 2 Engine cycle schematic view

Table 1 LE-9 engine specifications

Engine	LE-9	LE-7A	LE-5B
Engine cycle	Expander bleed cycle	Two-stage combustion cycle	Expander bleed cycle
Propulsive power (under vacuum) [kN]	1471	1098	137
Engine mixture rate [−]	5.9	5.9	5.0
Combustion pressure [MPa]	10.0	12.3 (main combustion chamber)	3.6
Specific impulse [sec]	426	440	448
Nozzle expansion ratio [−]	37	47	110
Weight [ton]	2.4	1.8	0.3
Length [m]	3.8	3.7	2.8
Application launch vehicle	H3 launch vehicle 1st stage	H2A/H2B launch vehicle 1st stage	H2A/H2B launch vehicle 2nd stage

For the LE-9 engine, we increased the size of the combustion chamber to a length approximately twice that of the LE-7A to secure the turbo pump driving energy required to increase the propulsive power. The combustion chamber is long in the axial direction, and therefore the axial directional acoustic mode frequency in the combustion chamber is low. Because acoustic modes in the axial direction, radius direction and circumferential direction are coupled in the combustion chamber, the mode density for a frequency becomes high when the axial directional acoustic frequency is low. This is an important characteristic for securing combustion stability as described below.

3. Combustion system test

3.1 Purpose of test

We started the development of the LE-9 engine with various element tests for understanding the characteristics of the phenomena occurring inside the engine, and established and improved the design analysis tools. In addition, material tests and new manufacturing technology development tests to accumulate base data for design and manufacturing were executed. Based on the data, prototype combustor system components were designed and manufactured. While the characteristics of the combustor system described below are difficult to evaluate in sub-scale element tests because of the scale effects, they are directly linked to the engine performance. Therefore, we set development steps where direct evaluations and verifications through full-scale combustion system tests through the use of a prototype engine were executed. **Table 2** summarizes the explanation and the purpose of testing for each characteristic.

Table 2 Purpose of combustion system test (full-scale test)

Item		Purpose of combustion system test (full-scale test)
Engine transient property	Properties of change with time in propulsive power, pressure and temperature at startup and shutdown	These properties cannot be understood by a sub-scale test because they largely depend on the flow path volume and the heat capacity (easiness to be heated and cooled) of components. Therefore, it was necessary to obtain data for analysis and verification in full-scale tests.
Combustion efficiency (combustion performance)	Index that indicates the ratio of the amount of heat energy actually generated from complete combustion of the propellant to the theoretically generated heat energy amount.	Evaluation in the order of 0.1% is necessary and therefore correct evaluation through analysis is difficult. This item cannot be evaluated by a sub-scale test due to the effects of the diameter and the length of the combustion chamber. Thus, it was necessary to perform verification through full-scale tests.
Combustion stability	Combustion pressure fluctuation level	- This item cannot be evaluated by a sub-scale test because the response characteristics change depending on the shape of the hundreds of injection elements, the arrangement of the resonator and the diameter of the combustion chamber. Thus, it was necessary to perform verification through full-scale tests. - It was necessary to obtain data for improving the prediction method in order to understand the tendency of the test.
Cooling property of combustion chamber	Combustion chamber wall temperature, heat amount acquired by coolant (hydrogen), and pressure drop between coolant inlet and outlet	The coolant temperature distribution (where the coolant temperature becomes higher at the inner circumference side and lower at the outer circumference side) formed in the flow path grows in the axial direction. Thus, it was necessary to obtain data for analysis and verification through full-scale tests.

3.2 Test diagram

Figure 3 shows the test diagram. The test does not include the turbo pump as the target, and is specialized for the downstream combustor system. Liquid hydrogen and liquid oxygen were pressurized in the tank on the upstream side of the engine and supplied to the engine in a high-pressure state. There was no turbo pump and therefore the turbine driving gas was discharged through the branch pipe. This test was implemented at the MHI Tashiro test facility (**Figure 4**).

3.3 Operating conditions

Figure 5 shows an example of the engine operation history. The names of the valves correspond to Figure 3. To prevent insufficient combustion chamber cooling, the CCV (Coolant Control Valve) was opened first to start the cooling of the combustion chamber, and then the MOV (Main Oxidizer Valve) and the MFV (Main Fuel Valve) were opened to start the rated operation. As shown in the combustion pressure history, the combustion pressure increased and decreased smoothly and there was no problem with the transient properties at startup and shutdown. The test time was determined by the restricted pressure tank capacity, but Figure 5 indicates that both the pressure and the temperature could maintain a steady state.

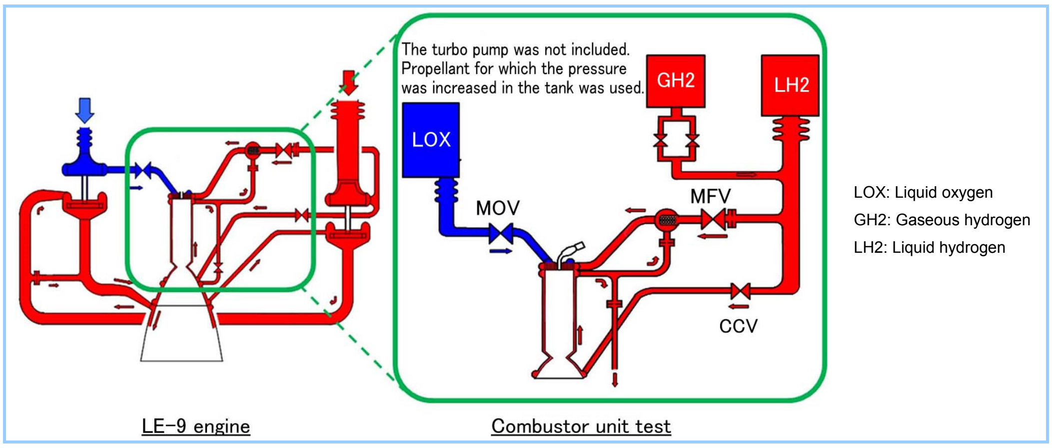

Figure 3 Combustor unit test diagram

Figure 4 Photograph of combustion test

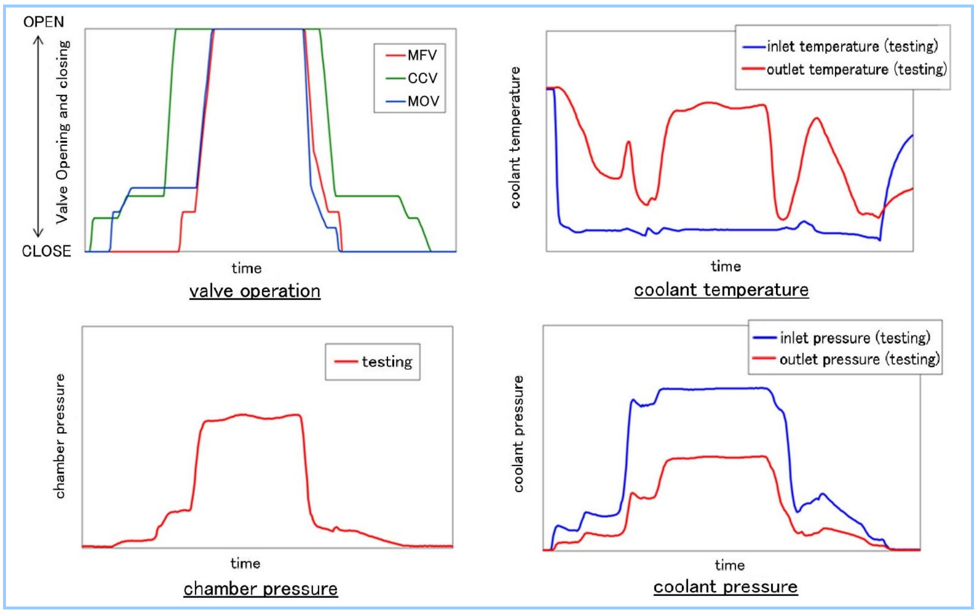

Figure 5 Engine operation history

3.4 Improvement in combustion stability

(1) Problem

Figure 6 shows the measurement results of the pressure fluctuation in the initial test configuration. The figure indicates that the combustion pressure fluctuated at a higher level than the LE-7A at a certain frequency and there was a strong peak on the oxygen side flow path inside the combustion chamber at the same frequency. In addition, the acceleration of the engine was greater in comparison with the conventional model and improvement in the stability was necessary.

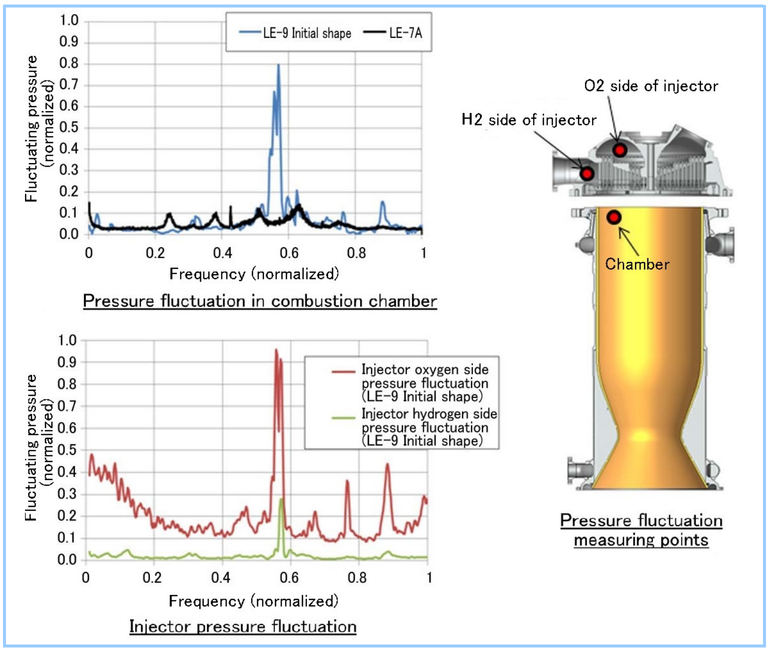

Figure 6 Pressure fluctuation (initial shape)

(2) Cause of instability

Considering the intensive fluctuation found on the oxygen side of the injector, the instability is suspected to have been caused by coupled phenomenon of the oxygen side acoustic mode inside the combustion chamber and that inside the injector.

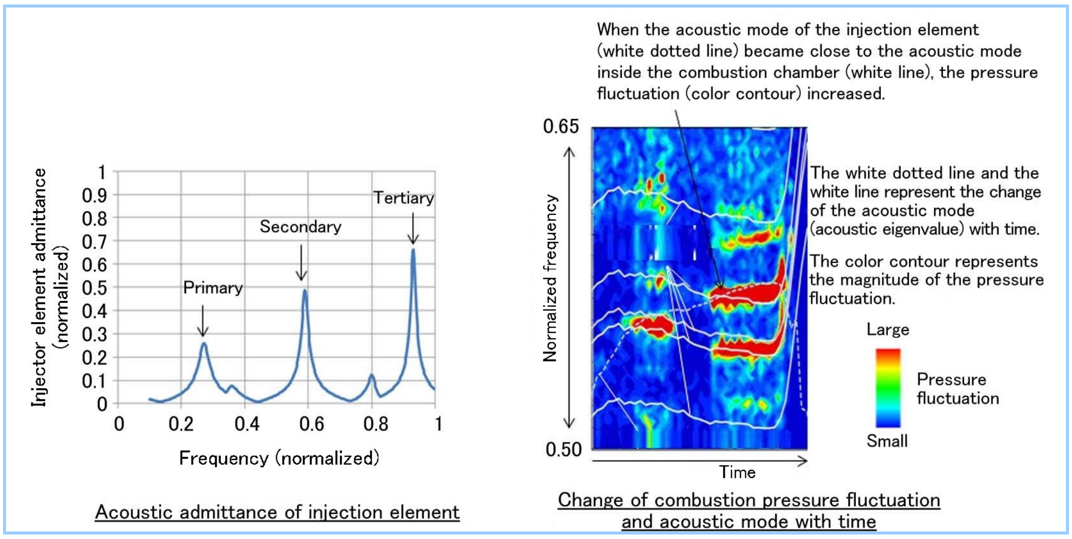

Figure 7 Cause of unstable combustion (initial shape)

Figure 7 shows the acoustic admittance inside the oxygen side injection element of the injector. The acoustic admittance is an index that represents the susceptibility of the pressure to acoustic fluctuation and can be calculated manually. The larger the acoustic admittance, the higher the tendency for instability. This figure indicates that the secondary mode frequency corresponded well to the peak of pressure fluctuation shown in Figure 6. For the primary and tertiary modes, only a slight peak is found in Figure 6. Therefore, it is considered that the fluctuation is determined not only by the acoustic characteristic of the injector, but also by the characteristics of the combustion chamber.

On the right side of Figure 7, the change with time in acoustic mode frequency inside the oxygen side injection element and inside the combustion chamber is plotted and the intensity of the combustion pressure fluctuation is shown using a color contour diagram. While the acoustic mode frequency of the injection element increases gradually as the speed of sound increases along with the lowering of the oxygen temperature, the acoustic mode frequency inside the combustion chamber decreases gradually as the speed of sound in the combustion chamber decreases along with the lowering of the mixture rate. The figures indicate that the combustion pressure fluctuation increased when the acoustic mode frequencies of the two approached each other. According to the above results, it was assumed that the instability was caused by the coupling of the oxygen side acoustic mode inside the injection element and that inside the combustion chamber.

(3) Improvement in shape

(a) Improvement in injection element

The acoustic admittance characteristic of the injection element was changed by reconsidering the flow path shape. As the principle of this change, two approaches were considered: displacing the admittance peak frequency and lowering the peak height. It was important to note the characteristic that the acoustic mode frequency in the axial direction was low and the mode density was high because the combustion chamber had a long shape. As shown in Figure 7, it was difficult to eliminate all coupling between the combustion acoustic modes even when the injection element acoustic admittance peak frequency was displaced, because many combustion chamber acoustic modes exist in a narrow frequency band due to coupling with a low-order L mode. Therefore, the shape was reconsidered in order to lower the admittance peak. **Figure 8** shows the injection element admittance of each configuration. The figure indicates that the acoustic admittance peak was separated into multiple parts by this change in the injection element shape that enhanced the dispersion and each peak height could be lowered.

(b) Improvement in resonator

Because a relatively large peak was also found for the tertiary mode of the injection element acoustic admittance as described below, the damping function of the resonator was enhanced as a countermeasure. The resonator is located on the circle between the injector and the combustion chamber as shown in Figure 1. The resonance frequency (damping frequency) of the resonator can be adjusted by changing the internal volume, and therefore resonators that are effective for multiple frequencies can be designed by combining and placing resonators with different shapes on the circle. **Figure 9** shows the absorption rate calculated by acoustic analysis. The higher absorption rate represents a higher-performance resonator with a high damping effect. Although conventional resonators concentrated the effects on the secondary mode of the injection element acoustic admittance as shown in the figure, the combination of shapes was reconsidered so that the resonator also became effective for the tertiary mode.

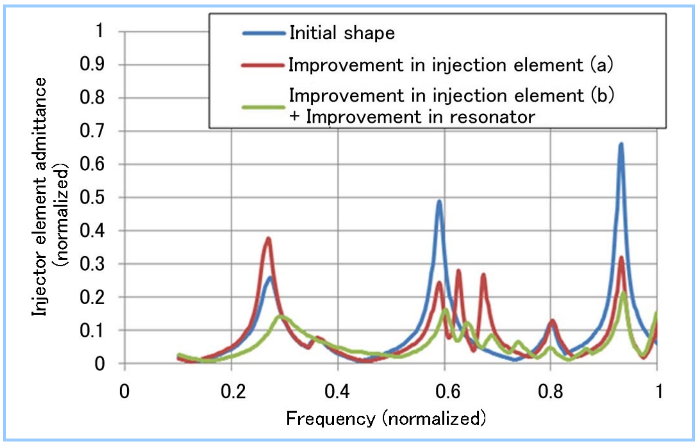

Figure 8 Improvement in injector element acoustic admittance

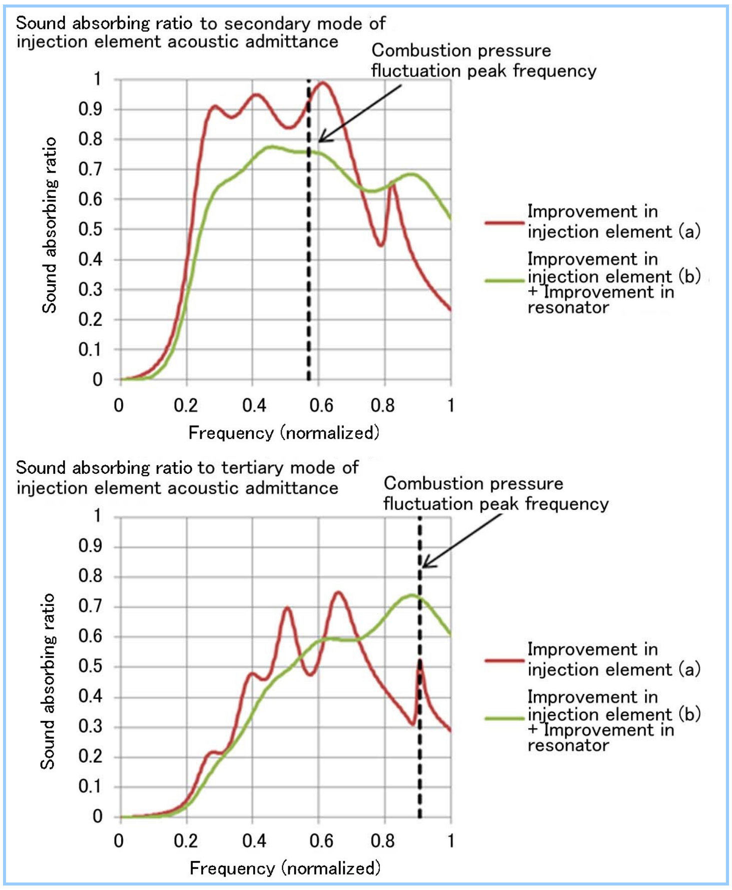

Figure 9 Broadening of resonator

(4) Verification of shape improvement effect

Figure 10 shows the combustion pressure fluctuation in a test where improvements in (a) injection element and (b) resonator shape are applied in sequence. By improving the injection element, the large fluctuation that was found with the initial shape around the dimensionless frequency of 0.6 was suppressed. The relatively large peak remaining around the dimensionless frequency of 0.9 was suppressed by improvement in the resonator. In this way, both improvements in the injection element and the resonator are effective for enhancement in combustion stability. Finally, the fluctuation is suppressed to the same level as the current LE-7A or smaller, and thus a plan to secure the combustion stability of the LE-9 engine was established.

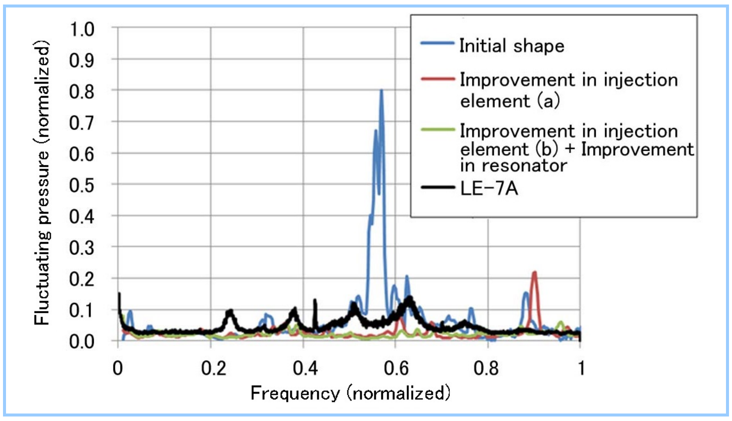

Figure 10 Verification results of improvement in combustion stability

(5) Establishment of combustion stability prediction method

Based on the test results, a combustion stability evaluation tool developed uniquely by MHI was established and verified. **Figure 11** shows the analysis flow diagram. The governing equation was an acoustic wave equation and a heat rate fluctuation characteristic equation. The heat rate fluctuation characteristic was set by combining the injection element acoustic admittance characteristic and the transfer function between the emission intensity (heat rate) and the pressure fluctuation obtained through a visualization combustion test that was implemented separately. The acoustic characteristic of the resonator was taken into consideration by setting the response characteristic obtained by acoustic analysis as the boundary condition. The speed of sound in the chamber, the density and the heat rate distribution were set using steady state combustion CFD. A complex eigenvalue analysis was performed using the above settings to calculate the resonance amplification ratio of the whole system. The resonance amplification ratio is an inverse of the damping ratio, and a higher resonance amplification ratio represents an unstable state. The right of Figure 11 compares the test results and the analysis results. The analysis captured the unstable frequencies and the magnitude relation between the peaks of the resonance amplification ratio was similar to the trend of the pressure fluctuation peaks observed in the test. For the LE-9 engine that is currently under development, the combustion stability can be predicted by performing similar analysis and comparing and evaluating the results.

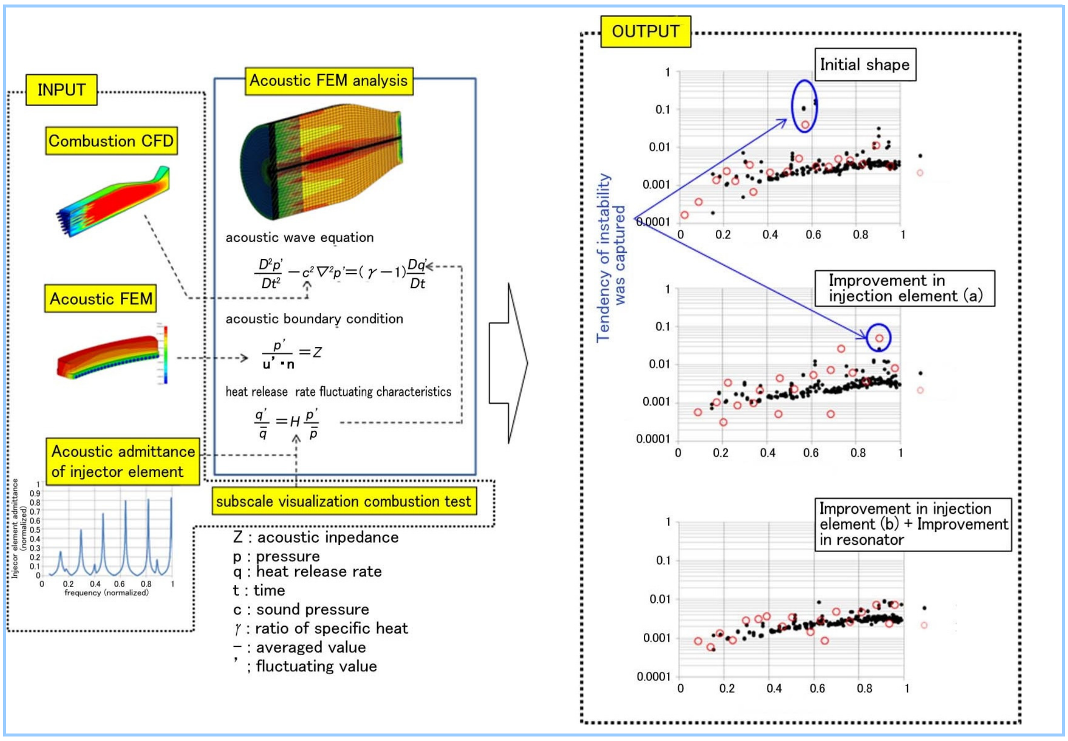

Figure 11 Combustion stability evaluation method (N-τ acoustic FEM analysis)

4. Conclusion

As a test for the development of the LE-9 first stage engine for the H3 launch vehicle, a full-scale combustion system test was implemented. Although an unstable phenomenon caused by the coupling of the acoustic mode inside the injection element and that inside the combustion chamber occurred in the test, the combustion stability was significantly and successfully improved due to improvement in the injector element shape and the resonator shape. As a result, the applicability to an actual engine was confirmed. In addition, a combustion stability evaluation tool was built, and it was confirmed that the tendency of the test could be reproduced. Currently the actual LE-9 engine is being manufactured, reflecting the improvements of the injector and resonator. A total engine system test is planned to be implemented in 2017.

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