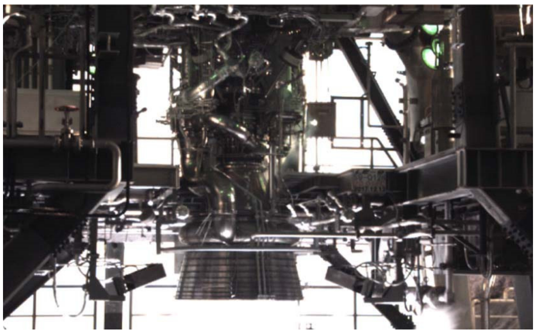
Development of Technologies for Prediction and Countermeasures for Combustion Stability for LE-9 Engine Booster Stage of H3 Launch Vehicle



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Mitsubishi Heavy Industries, Ltd. (MHI) is currently developing the LE-9 booster stage engine for the H3 launch vehicle in cooperation with the Japan Aerospace Exploration Agency (JAXA). Since the combustor of the LE-9 is larger than those found on conventional engines, it is necessary to suppress the significant pressure fluctuation (combustion instability) caused by unstable combustion. For this reason, we have newly developed a technology to disperse flow fluctuation using a combination of various injection element lengths and a technology to absorb pressure fluctuation using a resonator.(note1) This brought about significant improvement of combustion stability. With these key technologies, we have gained the prospective of the practical application of the LE-9, which is the world's first large-thrust engine that adopts the expander bleed cycle.(note2) The development of the LE-9 is proceeding smoothly toward the launch of the first vehicle in 2020.

(note 1) Resonator: Equipment that suppresses the amplification of pressure fluctuation caused by resonance
(note 2) Expander bleed cycle: One of the engine cycle types for liquid-fuel launch vehicles. Hydrogen used for cooling the combustion chamber is used for driving the turbo pump. Characteristically the expander bleed cycle is simple and has both intrinsic stability and low cost.

1. Introduction

One of the problems that can occur in the development of launch vehicle engines is combustion instability. Combustion instability is a phenomenon in which a large pressure fluctuation occurs in the combustion chamber due to unstable combustion. If combustion instability occurs, the amount of heat transferred to the wall surface of the combustion chamber increases under the influence of the pressure fluctuation, causing the wall surfaces of the combustion chamber and the injection element to melt, and in the worst-case scenario the engine can break. If such an event occurs in an actual engine combustion test, the development cost and development period will be significantly affected by design rework and additional tests. Therefore, from the early stages of development, it is important to design an engine that ensures stable combustion without combustion instability.

However, since this event is affected by the shape of several hundred injection elements and the size of the combustion chamber, it is difficult to directly verify in a sub-scale combustion test (combustion test of one to several injection elements) that can be implemented during the initial stages of engine development. Advance prediction and preliminary countermeasures against combustion instability require advanced technology since it is a complicated phenomenon in which combustion, fluid, and acoustic phenomena interact with each other, because there are many influence factors and because various combustion instability frequencies and modes can be generated.

Therefore, we developed the following technologies for improving the combustion stability of the LE-X technical verification engine, which targets preliminarily verification of the design

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technology of the LE-9.

- Analysis of combustion instability generation mechanism
- Development of prediction technology for combustion instability
- Development of technological countermeasures against combustion instability

This paper reports on the development of these technologies related to combustion instability.

2. Analysis of combustion instability generation mechanism

To develop an engine that realizes stable combustion without generating combustion instability, it is necessary to identify the cause of combustion instability, eliminate it and add acoustic damping to the combustion chamber. In addition, to implement these countermeasures, a technology for predicting the frequency band of the generation of the combustion instability is required. For the development of these technologies, it is necessary to clarify the generation mechanism of combustion instability of a launch vehicle engine.

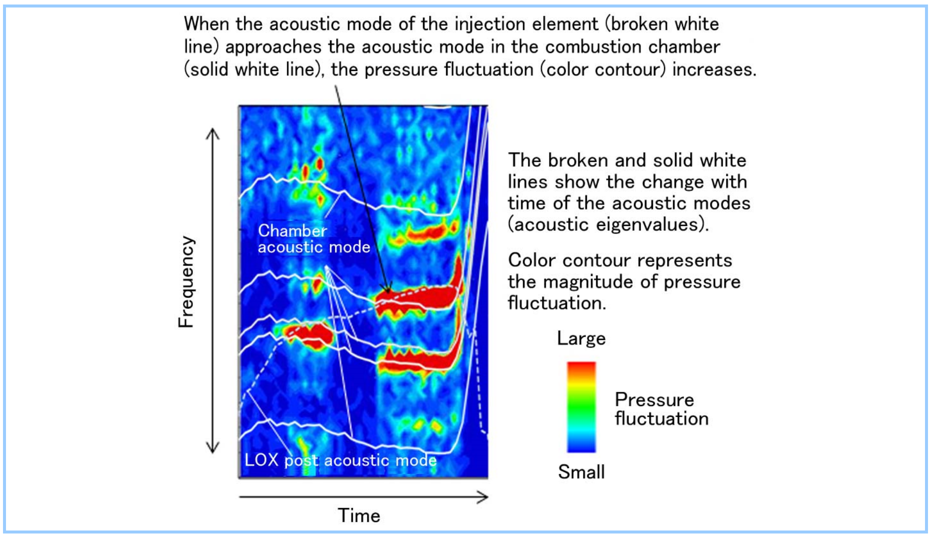

Figure 1 Combustion chamber pressure fluctuation measurement results of combustion test of LE-X (without countermeasures against combustion instability)

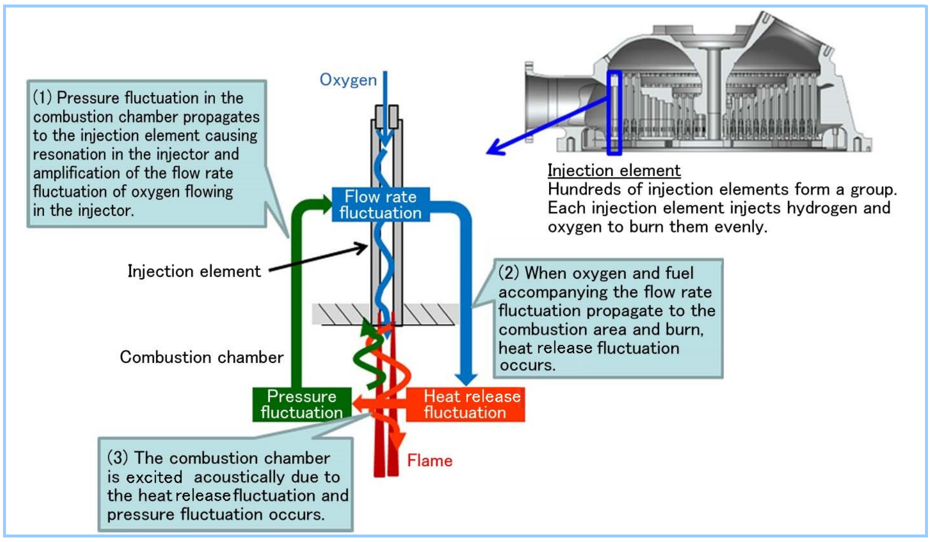

Figure 2 Mechanism of injection coupled combustion instability

As such, by analyzing engine combustion test data including conventional models, the mechanism of combustion instability was analyzed. **Figure 1** shows the combustion chamber pressure fluctuation measurement results of a combustion test of the LE-X (without countermeasures against combustion instability) as a representative example of combustion instability. In this figure, the magnitude of the pressure fluctuation inside the combustion chamber (color contour) is shown with respect to time (horizontal axis) and frequency (vertical axis). The acoustic resonance frequency of the combustion chamber is indicated by a solid white line, and the acoustic resonance frequency of the injection element is indicated by a broken white line. When the acoustic resonance frequency of the combustion chamber approaches the acoustic resonance frequency of the injection element, combustion instability occurs, and the pressure fluctuation increases. This suggests that when the pressure fluctuation in the combustion chamber couples with the injection element acoustically, the generation of combustion instability is triggered (hereinafter referred to as injection coupled combustion instability). As shown in **Figure 2**, the mechanism of injection coupled combustion instability is considered as follows.

(1) Pressure fluctuation in the combustion chamber propagates to the injection element causing resonation in the injection element and amplification of the flow rate fluctuation of oxygen flowing in the injection element.

(2) When oxygen and fuel accompanying the flow rate fluctuation propagate to the combustion area and burn, heat release fluctuation occurs.

(3) The combustion chamber is excited acoustically due to the heat release fluctuation and pressure fluctuation occurs.

The pressure fluctuation, flow rate fluctuation, and heat release fluctuation form a relationship in which they amplify mutually in the feedback loop of phenomena (1) to (3), and the pressure fluctuation grows leading to combustion instability.

As a result of analysis of the engine combustion test, it seemed that there was a high necessity to prevent the injection coupled combustion instability that occurs in many cases. Therefore, in the development of the LE-9, the development of technologies for prediction and countermeasures against combustion instability was undertaken, targeting injection coupled combustion instability.

3. Development of prediction technology for combustion instability

It is important to predict the generated frequency to take countermeasures against combustion instability. This is because it is not realistic to implement countermeasures for all frequencies and it is necessary to determine the target frequency.

Therefore, in developing the LE-X, we developed a method for predicting the generated frequency of injection coupled combustion instability. **Figure 3** outlines the combustion stability prediction technology.

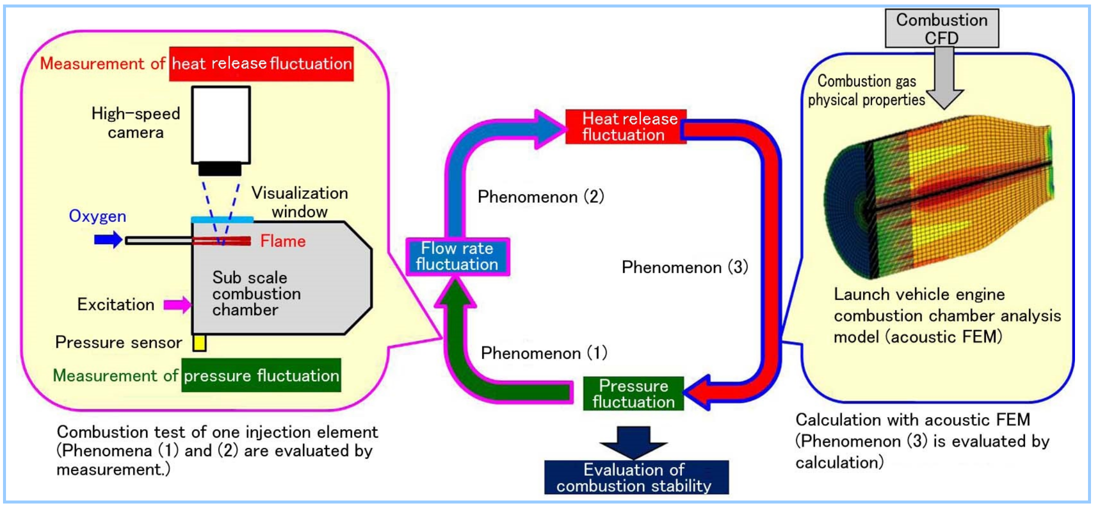

Figure 3 Outline of combustion stability prediction technology

By appropriately predicting phenomena (1) to (3) of injection coupled combustion instability in Chapter 2, combustion stability can be evaluated. However, phenomenon (2) in particular is related to the complicated dynamic behavior of combustion, and it was difficult to predict exactly by analysis and theory.

Therefore, regarding phenomena (1) and (2), a high-pressure combustion test of single injection element was conducted at JAXA Kakuda Space Center and direct measurement and evaluation were performed. An injection element was tested on the sub-scale combustor, and the combustion chamber was separately acoustically excited during the combustion test to apply pressure fluctuation. By measuring the pressure fluctuation inside the combustion chamber with a pressure sensor and photographing the flame with a high-speed camera through a visualization window, the heat release fluctuation (luminescence intensity(note3)) at pressure excitation was measured. As a result, the response characteristics of heat fluctuation to pressure fluctuation (the magnitude of the heat release fluctuation amplitude with respect to the pressure fluctuation amplitude and the delay in the response time of the heat release fluctuation with respect to the pressure fluctuation) were measured, and phenomena (1) and (2) necessary for stability evaluation were evaluated.

Phenomenon (3) was evaluated by acoustic FEM(note4) using wave equations. For the combustion gas physical properties (acoustic velocity, density) in the combustion chamber, the results of the combustion CFD(note5) that was separately performed were used.

As described above, we developed a stability evaluation method combining measurement and analysis and verified its prediction accuracy in the LE-X single combustor test.

(note 3) Luminescence Intensity: The intensity of the light of a specific wavelength emitted by the combustion reaction is correlated with the magnitude of the heat release. The heat release distribution can be measured by high-speed camera photography using a filter that allows only this specific wavelength to pass through.

(note 4) Acoustic FEM: Finite element method for solving acoustic wave equations. Acoustic propagation phenomena (pressure fluctuation) using a computer.

(note 5) Combustion CFD: Computational fluid dynamics for solving a flow field including the combustion reaction. Flow and combustion reactions are calculated using a computer.

4. Development of technological countermeasures against combustion instability

Figure 4 presents an outline of the technology for countermeasures against injection coupled combustion instability. We newly developed two technologies of dispersing flow rate fluctuation using a combination of different injection element lengths and absorbing pressure fluctuation using a resonator.

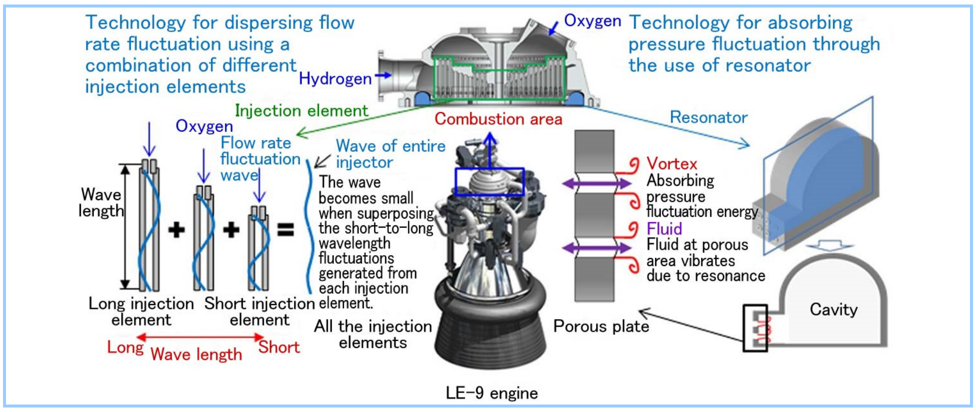

Figure 4 Outline of technology for countermeasures against combustion instability

4.1 Technology for dispersing flow rate fluctuation using a combination of different injection element lengths

Regarding phenomenon (1), the fact that the pressure fluctuation in the injection element amplifies the flow rate fluctuation of oxygen by resonance is focused on. Specifically, if it is possible to suppress the amplification of flow rate fluctuation caused by resonance in the injection element, combustion instability can be suppressed. Therefore, we developed a technology to disperse the wavelength of the flow rate fluctuation by combining different injection element lengths to suppress the overall flow rate fluctuation when many injection elements are combined.

Figure 5 illustrates the effects of countermeasures against combustion instability for an injection element. Since the injection element without countermeasures uses multiple injection elements of the same length, when pressure fluctuation is applied from the combustion chamber and resonates in the injection element, flow fluctuation of the same wavelength flows out of the injection element at the same timing. As a result, flow fluctuations flowing out from a large number of injection elements strengthen each other, resulting in excessive flow rate fluctuation overall and causing large fluctuations of the heat release and pressure. The injection element with countermeasures has an appropriate variation in the length of the injection element as a result of acoustic examination. Waves with short wavelengths occur in short injection elements and waves with long wavelengths occur in long injection elements, so combining long and short wavelength waves suppresses the flow rate fluctuation of all the injection elements. As a result, it becomes difficult for large heat release fluctuation to occur, and combustion instability can be suppressed. In the design of the LE-9, this technology was used to optimize the length of the injection elements.

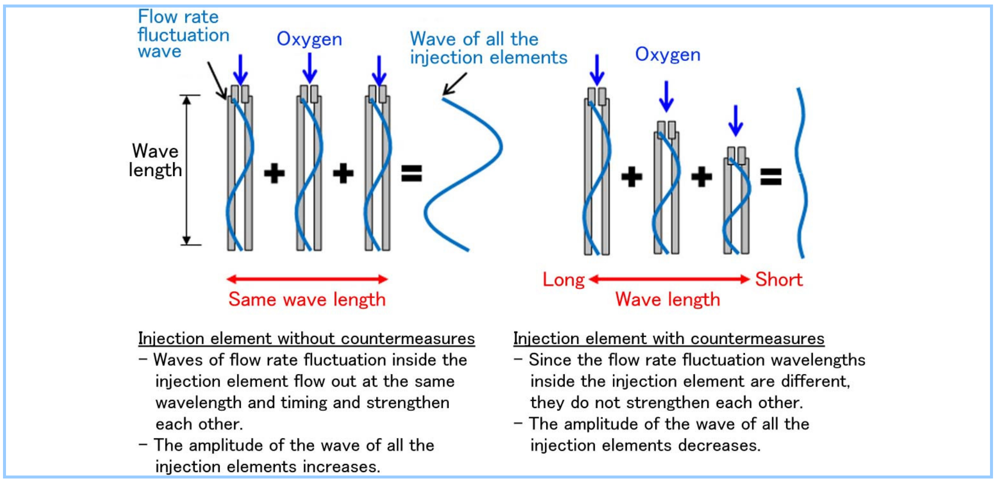

Figure 5 Effect of countermeasures against combustion instability for injection element

4.2 Technology for absorbing pressure fluctuation using a resonator

As a device that absorbs the pressure fluctuation in the combustion chamber, we developed a resonator attached near the injection surface of the combustion chamber. A porous plate is attached to the entrance of the resonator to absorb pressure fluctuation with vortices generated when the fluid enters and exits the perforated holes due to the acoustic resonance phenomenon. The larger the vortex generated when the fluid enters and exits the perforated holes, the greater the acoustic attenuation, but the actual engine operates a high-pressure, and the pressure fluctuation amplitude is larger than that under an atmospheric pressure conditions, so the vortex and acoustic attenuation that occurs grows.

For this reason, it is not possible to use acoustic attenuation measured by an element test under atmospheric pressure conditions as the evaluation value of the actual equipment. Therefore, at the JAXA Kakuda Space Center, the acoustic attenuation of the resonator under pressure fluctuation equivalent to the actual equipment was measured. **Figure 6** shows the resonator acoustic attenuation measuring device and the measurement results. Nitrogen was flowed into the device under a high-pressure condition and a siren wheel was used to perform tremble acoustic pressure excitation. A pressure fluctuation sensor was attached at the inlet and the inside of the resonator to measure the amplification factor of the internal pressure fluctuation amplitude with respect to the pressure fluctuation amplitude at the inlet to evaluate the acoustic attenuation. Separately, the result obtained by Guess's acoustic attenuation evaluation formula (semi-theory, semi-experiment)[5] are also shown. It was confirmed that the evaluation formula and the measurement results were roughly in agreement and that the acoustic attenuation was proportional to the Mach number of the flow velocity variation of the fluid passing through the perforated holes.

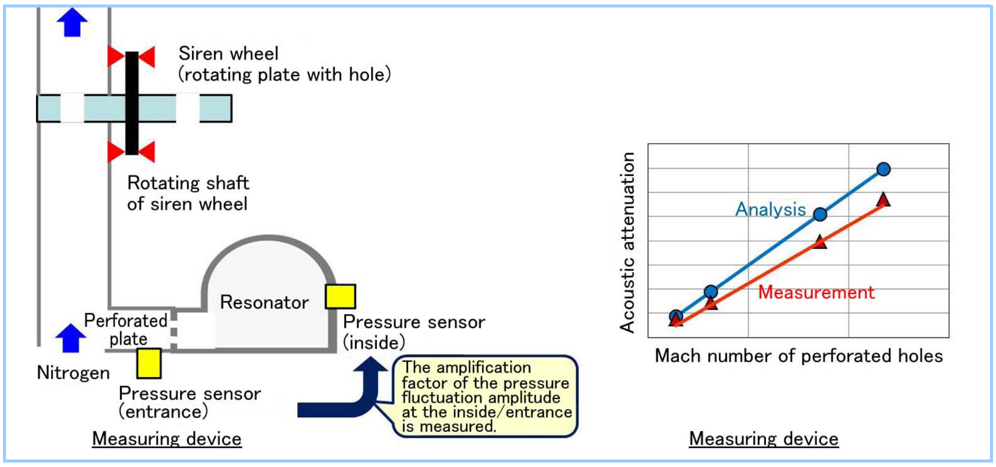

Figure 6 Resonator acoustic attenuation measuring device and measurement results

Therefore, when evaluating the acoustic attenuation of the resonator of actual equipment, the Mach number of the perforated holes was approximated from the pressure fluctuation assumed by the actual machine, the sound speed, the density and the perforated plate opening ratio, and the acoustic attenuation was evaluated using the device in Figure 6. In the design of the LE-9, we attempted to optimize acoustic attenuation by adjusting the porosity of the perforated plate of the resonator using this evaluation method.

In an actual engine, combustion instability of multiple frequencies may occur, and it was assumed that multiple types of resonators are simultaneously used to suppress each frequency. At this time, since there was a possibility that the different resonators acoustically interfere with each other and the performance might deteriorate as a result, acoustic characteristics (acoustic absorption coefficient) at the time when multiple types of resonators were simultaneously used in the element test were evaluated. **Figure 7** presents an element testing apparatus in which two types of resonators are arranged in a circumferential shape. The type A resonator and type B resonator were arranged alternately in the circumference, and pressure excitation was applied from the top surface with a speaker. Using the pressure fluctuation data measured with pressure sensors arranged in two rows, the acoustic absorption coefficient for acoustic waves propagating outward from the disc center was evaluated. In addition, we performed analysis using acoustic FEM for element tests. **Figure 8** illustrates the measurement results and analysis results. The acoustic absorption rate of the test generally agrees with that of the analysis. It was confirmed that when multiple resonators are arranged, the valley of the acoustic absorption coefficient generated when the resonator is used alone is filled and a high acoustic absorption rate can be obtained in a wider range than when using a resonator alone. In addition, knowledge on the number and arrangement of resonators necessary for spatial distribution and frequency of pressure fluctuation amplitude was obtained through this element test and analysis. As a result, the number and arrangement of resonators could be designed for the LE-9 to efficiently absorb pressure fluctuations.

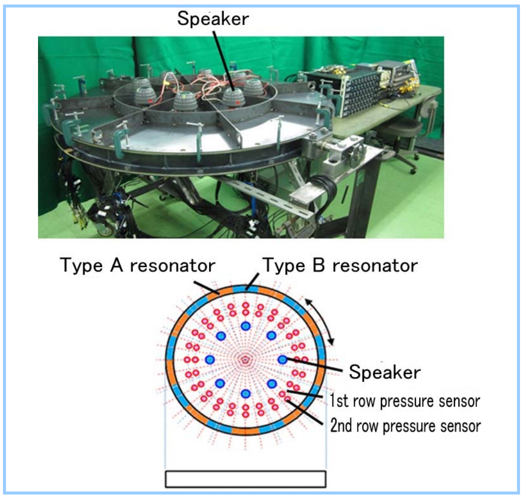

Figure 7 Element test apparatus in which two types of resonators are arranged circumferentially

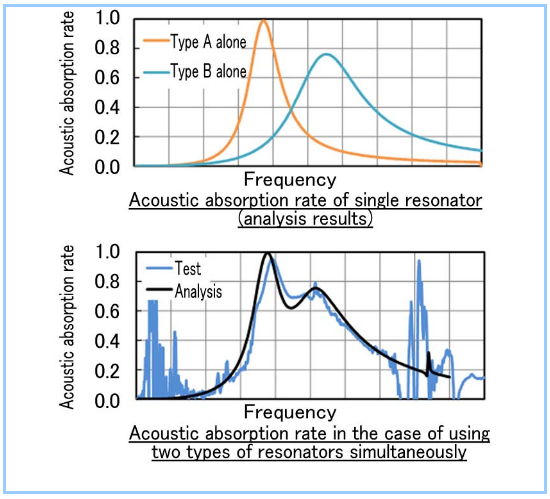

Figure 8 Acoustic absorption rate in the case where two types of resonators are simultaneously used

5. Verification with actual engine

A solo combustor test of the LE-X technical verification engine was carried out at our Tashiro test site (**Figure 9**). **Figure 10** provides the combustion chamber pressure fluctuation spectrum measurement results in the combustion test. The configuration without countermeasures experienced large pressure fluctuation (combustion instability) in mode A and mode B. However, in the case of the configuration with countermeasures on the injection element and the resonator, the combustion instability completely disappeared in both mode A and mode B, and the pressure fluctuation level could be suppressed to 1/100.

Figure 11 gives the verification results of the combustion instability prediction technology. The resonance magnification is the reciprocal of the damping ratio, and the higher the value, the lower the stability. In the analysis, the tendency where the pressure fluctuation level (resonance magnification) becomes larger in both mode A and mode B is consistent with the measurement.

The magnitude relation of the resonance peaks resulting from the analysis coincided with the trend of the fluctuation pressure peaks obtained through the test.

As a result of development using these technologies for prediction and countermeasures against combustion instability that were developed with the LE-X, it was verified that no combustion instability occurred in the actual engine test of the LE-9 engine, and the combustion stability was greatly improved.

Figure 9 LE-X combustor test

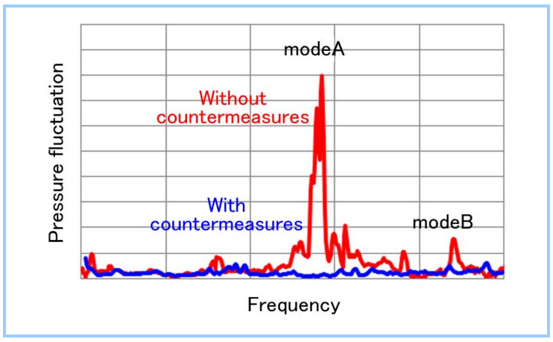

Figure 10 Combustion chamber pressure fluctuation spectrum measurement results in combustion test

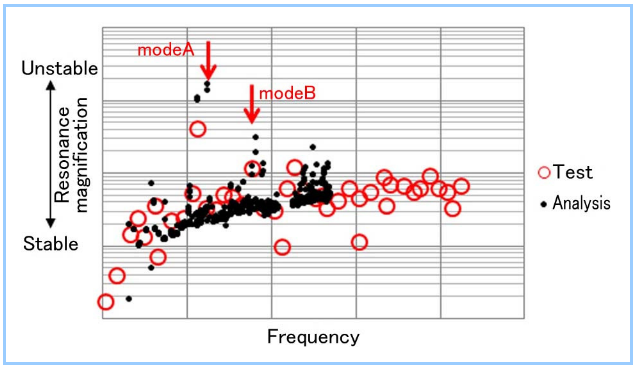

Figure 11 Technology verification results of prediction of combustion instability

6. Conclusion

We developed technologies for improving combustion stability in the development of the LE-X technology verification engine aiming at preliminary verification of the design technologies for the LE-9. A method to predict the frequency band where combustion instability occurs was established by stability analysis. Furthermore, a design technology to reduce the combustion instability level by tuning the acoustic characteristics of the injection element was developed, and a method to predict the acoustic characteristics of resonators with high accuracy was established. In addition, we applied these technologies to an actual engine and verified their effectiveness.

Using these technologies, we have gained the prospective of the practical application of the LE-9, which is the world's first large-thrust engine that adopts the expander bleed cycle. The development of the LE-9 is proceeding smoothly toward the launch of the first vehicle in 2020.

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