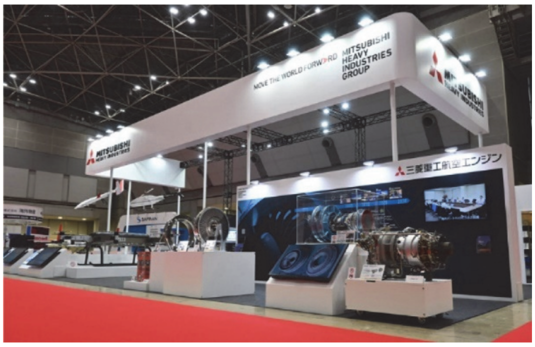
Development of Technology for Low-pressure Turbines and Combustors for Next Generation Civil Aircraft Engines



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As the aviation industry continues its efforts to reduce CO_2 emissions, achieving both high efficiency and high durability in next-generation civil aircraft engines is demanded. Mitsubishi Heavy Industries Aero Engines, Ltd. (MHIAEL) is working to enhance its capabilities in developing low-pressure turbines and combustors, considering these as a strategic area. Regarding low-pressure turbines, multiple tests were conducted, aiming at verification of high-efficiency airfoils, verification of seal designs for optimization of secondary air system, verification of vibration control technology of rotor blades. System demonstrations were also carried out using an actual engine, resulting in enhanced capability in the development of low-pressure turbines. Regarding combustors, technology to machine cooling holes using lasers and water jets and a heat-resistant ceramic coating technology have been developed. MHIAEL will further enhance its technological capabilities with the aim of adopting these technologies to next-generation civil aircraft engines.

1. Introduction

In recent years, the aviation industry has reached a major turning point in sustainable development. As the need to address climate change grows, reducing CO_2 emissions from aircraft operations has emerged as a critical issue. As international agreements and regulations have become increasingly stringent, engine manufacturers urgently need to develop new technologies to reduce environmental impact.

Mitsubishi Heavy Industries Aero Engines, Ltd. (hereinafter referred to as MHIAEL) has been involved in engine combustor development projects, including the internationally co-developed V2500 engine whose development began in the 1990s and the PW1100G-JM in recent years. As a result, MHIAEL now possesses the world's most advanced manufacturing technologies. In addition, MHIAEL has enhanced its low-pressure turbine (hereinafter referred to as LPT) design technology based on its developmental experience with the power turbine for the PW210 helicopter engine. Currently, MHIAEL is expanding its business primarily in the areas of combustors and LPTs (**Figure 1**).

To improve propulsion efficiency, bypass ratio of civil aircraft engines has increased. The importance of LPT, which drive the fans, has grown, and increasing both efficiency and structural integrity is needed. In addition, since the combustor is one of the hottest parts in the engine, improving environmental compatibility without compromising durability is needed even though engine load to improve fuel efficiency increases.

To contribute to the reduction of environmental impact, MHIAEL has enhanced its design and manufacturing technologies for LPTs and combustors through its research and development and engine development programs. For next-generation engine development programs, this is expected to contribute to the entire development process, including component technologies, product

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development, and test demonstration in corresponding areas. To achieve this, strengthening integration capabilities is essential. This report presents recent activities by MHIAEL to enhance development capabilities.

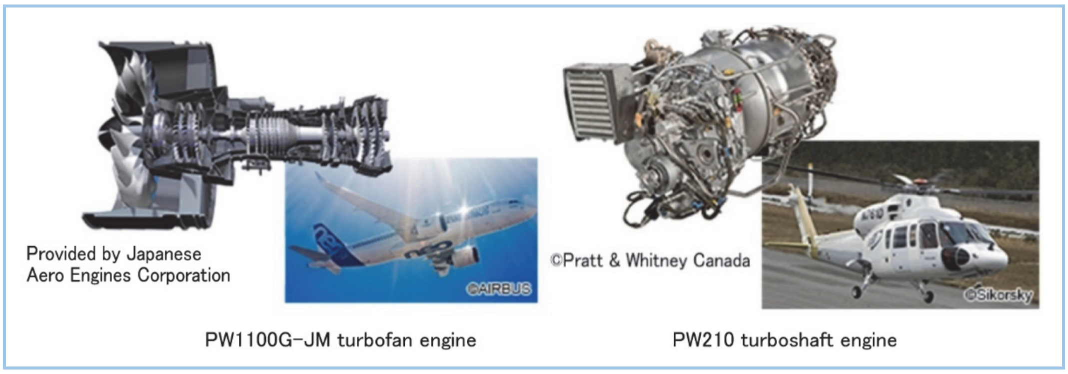

Figure 1 PW1100G-JM and PW210

2. LPT technology

An LPT is a module located at the rear of the engine, and is primarily responsible for driving the fan using high-temperature, high-pressure gas supplied from the high-pressure turbine (hereinafter referred to as HPT) outlet. As engine designs with high bypass ratios continue to advance in response to decarbonization and fuel cost saving needs, LPT has become increasingly important and achieving even higher efficiency is needed. In recent years, the trend for higher speed turbines like geared turbofans has advanced, and efficiency is expected to improve. However, increased pressure ratio per stage and increased stress on rotating components have led to stricter structural and vibratory requirements. To address these issues, MHIAEL has promoted the development of component technologies such as aerodynamic technology, leakage flow control technology, and blade vibration control technology. In addition, MHIAEL has successfully completed demonstration testing using an actual engine.

2.1 Aerodynamic design technology

Aiming to improve the aerodynamic performance of LPTs, MHIAEL has been working on demonstration tests for high performance airfoils under aerodynamic conditions closely representing actual engines. LPTs are critical components that drive fans and low-pressure compressors. Improving their performance directly contributes to improvement in overall engine fuel efficiency. In particular, profile loss (airfoil surface friction loss), which is the main loss factor of LPT airfoils, is pronounced in high-aspect-ratio airfoils where chord length relative to span is large. Furthermore, loss tends to increase in high-altitude environments where the Reynolds number is low. Therefore, controlling profile loss by optimizing load distribution of the airfoil is important.

To address the above issues, a performance comparison between aft-loaded airfoils and front-loaded airfoils (airfoils where surface velocity peak point is located either in the aft or front) was first carried out using the linear cascade test as shown in **Figure 2**. In the test, which was conducted under conditions equivalent to those of an actual engine, pressure loss was evaluated based on pressure measurements at the point of entry and exit of the airfoils. According to the results, the front-loaded airfoil showed a lower pressure loss compared to the aft-loaded airfoil. In addition, a smaller deceleration rate on the suction side of the airfoil contributed to a reduction in profile loss.

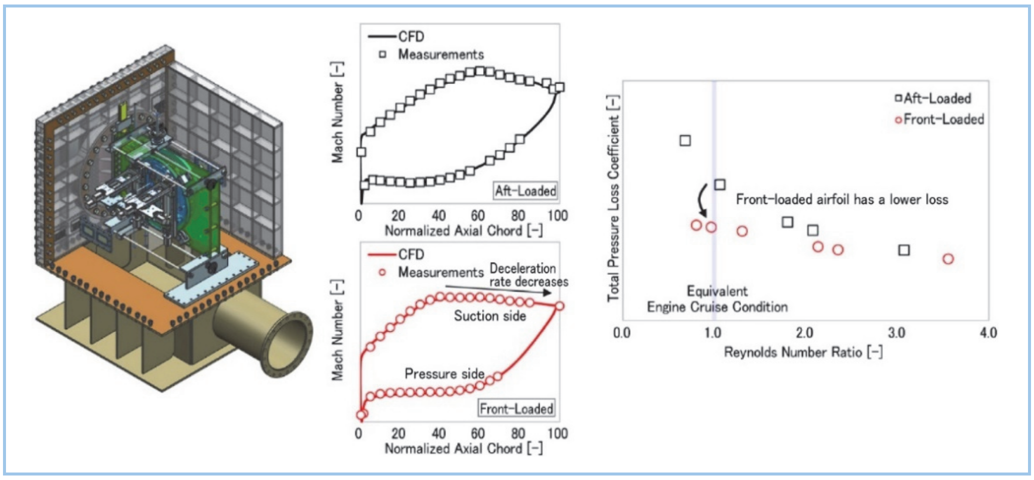

Figure 2 Bird's-eye view of test equipment for linear cascade test and test results

Next, performance of a front-loaded airfoil in a multi-stage LPT was evaluated by the rotating test as shown in **Figure 3**. Pressure and temperature distributions at the LPT inlet and exit, as well as on the airfoil surface, were measured with a front-loaded airfoil specifically adopted in the rear stage and compared with the CFD analysis. The measurement results agreed well with the analysis results, and variation in LPT efficiency with respect to pressure ratio also quantitatively matched. Achievement of the designed performance of the front-loaded airfoil, even in a multi-stage LPT, could be confirmed.

These test results clearly indicate that a front-loaded airfoil can effectively reduce loss compared to a conventional aft-loaded airfoil and contribute to the improvement of the aerodynamic performance of LPTs. [1]

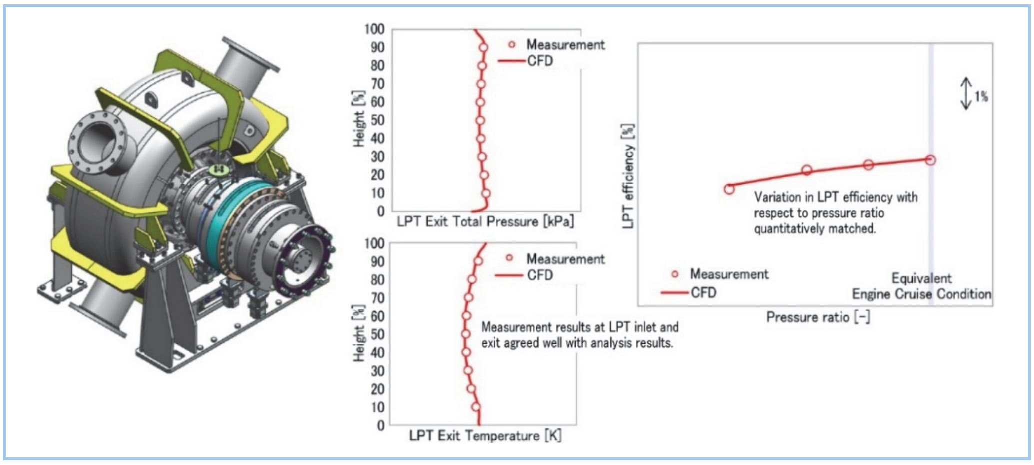

Figure 3 Bird's-eye view of test equipment for rotating test and test results

2.2 Seal-based leakage flow reduction technology

In order to improve the efficiency of LPTs, reducing secondary air flow is important. Secondary air extracted from the compressor flows through cavities around the disk and case of the LPT, eventually mixes with the mainstream flow and is then discharged externally. By reducing the amount of secondary air, (i) improvement in engine cycle efficiency due to a reduction in the secondary flow from the compressor, and (ii) reduction in mixing loss with the mainstream flow can be expected, leading to overall improvement in performance. Additionally, secondary air also plays a role in preventing the ingestion of high-temperature gas in the mainstream flow into the cavities around components such as the disk and case, and thereby suppresses component heating. In particular, ingestion of mainstream flow gas through the gap (rim seal) between the blade and vane can heat the disk, a critical component, which may cause a fracture in the worst case. Therefore, a design that suppresses hot gas ingestion using secondary air is required. In order to achieve higher LPT efficiency while preventing disk heating, accurately predicting the amount of secondary air volume needed to suppress hot gas ingestion from the rim seal is essential. Particularly, the first stage stator vane of the LPT may have a large vane width and thickness with fewer airfoil counts, due to design constraint of bearing compartment and oil supply/discharge tubes. In such case, the pressure field induced by the first stage stator vane may cause mainstream flow gas ingestion through the rim seal.

Research on hot gas ingestion through the rim seal is actively being conducted by engine manufacturers and universities. However, predicting this ingestion by numerical calculations is considered difficult due to the complexity and unsteadiness of the flow field caused by interaction between the mainstream flow gas and secondary air. As such, a component test simulating the flow field around the rim seal of an actual engine, as shown in **Figure 4**, was conducted to evaluate hot gas ingestion characteristics. The test simulated 20% height of the first stage vane, blade and the second stage vane of an actual engine, with the rim seal equipped with an independent air supply system. CO_2 gas was mixed into the secondary air supply system and CO_2 concentration was measured at the test area in order to evaluate the characteristics of a mainstream flow gas ingestion. From the results, the measured amount of mainstream flow gas ingestion was confirmed to be less than the design target for the assumed amount of purge air at the measurement point on the inner side of the rim seal. Improved prediction accuracy of the amount of secondary air was achieved.

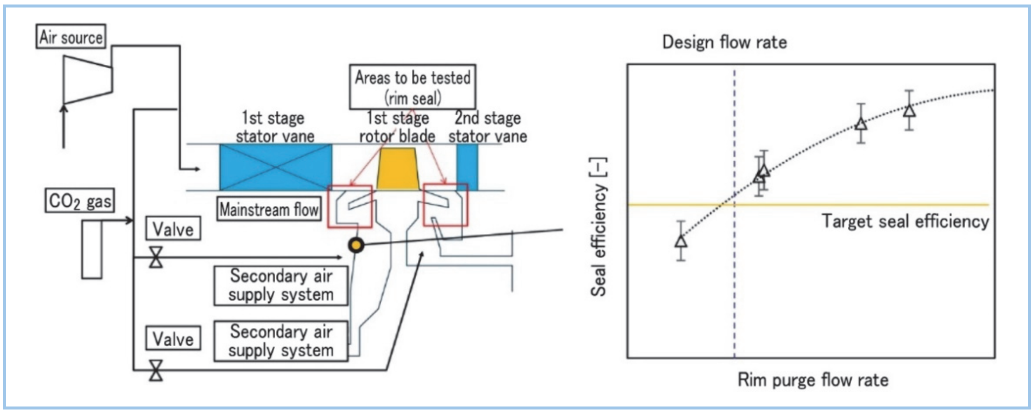

Figure 4 Rim seal test schematic diagram and test results

2.3 Blade vibration control technology

One of the primary technological issues of LPT rotor blades is the control of blade vibration. LPT rotor blades, which have a higher aspect ratio compared to HPT rotor blades, have a lower natural frequency, raising concerns about resonance with the engine rotational speed. Consequently, LPT rotor blades have a tip shroud, and are designed to reduce vibration response by interlocking the tip shroud to increase the natural frequency and utilize damping through friction. In addition, friction damping provided by the under-platform damper and blade retaining component also contributes to the reduction of vibration stress.

In order to verify the effectiveness of these damping mechanisms in advance, the scale component test as shown in **Figure 5** was conducted. In this test, damping characteristics of the tip shroud and under-platform damper were obtained under conditions close to an actual engine environment by intentionally applying excitation forces using multiple air excitation nozzles to single-stage blades rotating inside the vacuum chamber. As indicated from the obtained data, the actual engine test blade is expected to have sufficient integrity. Based on this, vibration design technology for high-aspect-ratio LPT rotor blades was established.

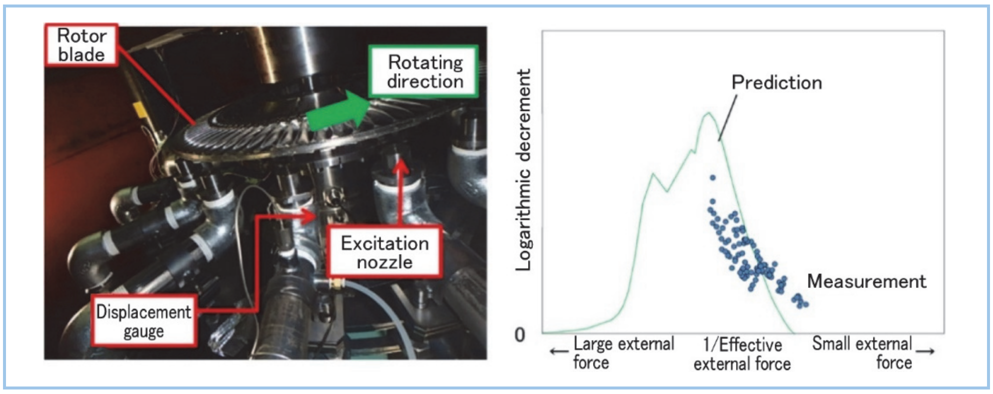

Figure 5 Illustration of rotor blade vibration test sample and test results

2.4 Demonstration of technology using actual engine testing

By using the technology verified in the component test, an LPT module for actual engine testing was developed. This module, which was designed to be compatible with the LPT module of an existing engine, was installed in place of an existing engine LPT module and demonstration testing of the technology was conducted. The demonstration testing had three objectives: (1) verification of aerodynamic performance, (2) verification of the secondary air system and heat transfer system, and (3) verification of blade vibration design technology. To achieve these, over 1,000 special measurement points were set on the LPT module. In addition to the conventional (intrusive) measurements using strain gauges and a telemetry system, a non-intrusive stress measurement system (hereinafter referred to as NSMS) was applied to all stages to assess variation across all rotor blades for the above objective (3).

The testing program included a performance acquisition test at rated points, a thermal survey test to obtain steady-state and transient temperature and pressure characteristics, and a vibration survey test sweeping the rotational speed across the operating range. The tests were successfully completed. Over 94% of all measurement points survived (in particular, all strain gauges and NSMS values survived), demonstrating the high level of special measurement technology possessed by MHIAEL. Main results are shown in **Figure 6**.

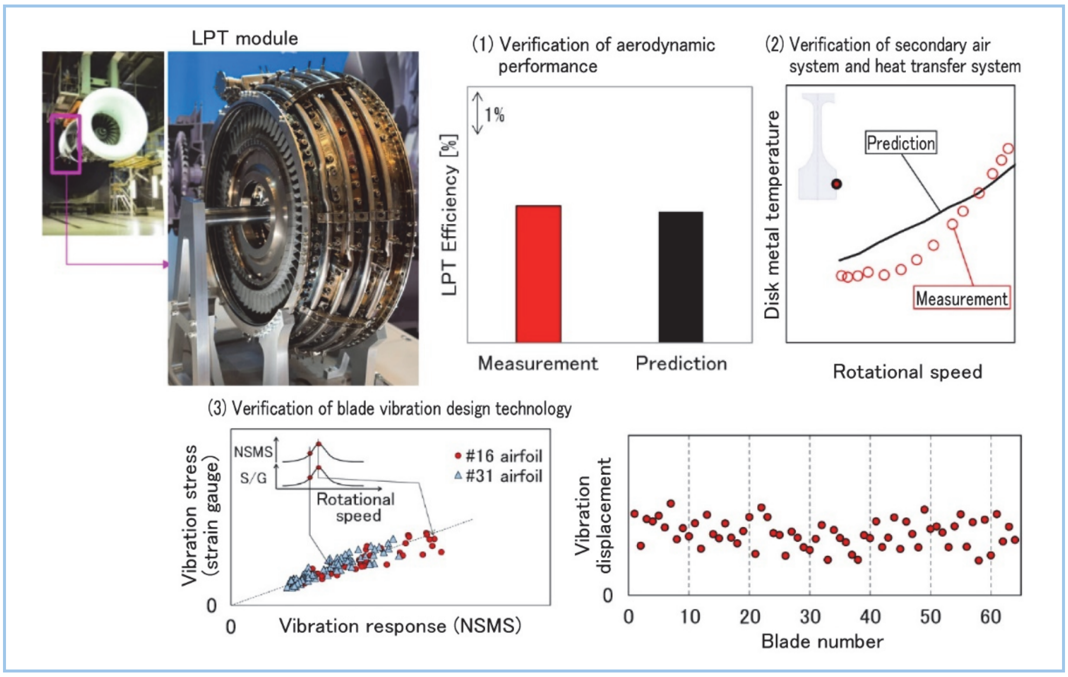

Figure 6 Demonstration testing of low-pressure turbine system using actual engine and test results

(1) Verification of aerodynamic performance: LPT efficiency obtained from engine cycle analysis using the measurement results closely matched the CFD analysis results, confirming practicality and reliability of the front-loaded airfoil.

(2) Verification of secondary air system and heat transfer system: From the temperature measurements of the disk, predicted and actual measurements closely matched under design conditions, but differed under off-design conditions. By utilizing these findings, accuracy of the evaluation system was improved.

(3) Verification of blade vibration design technology: Measurement results from the strain gauge and NSMS demonstrated high correlation, confirming effectiveness of NSMS. Furthermore, NSMS could quantitatively confirm variations in the peak response (displacement) of each blade. Similarly, variations in the natural frequency and total damping could also be quantitatively confirmed. [2]

These measurement results provide valuable data which can only be obtained from an actual engine. Using this data, MHIAEL will continue to improve various prediction technologies and design highly competitive LPT modules for next-generation civil aircraft engines that meet the demand for efficiency, durability, and weight at a high level.

3. Combustor technology

MHIAEL has supplied combustors to global partner companies for many years. In recent years, the "New Combustor Center" was established in the Nagasaki District to meet the strong demand for short- and medium-range civil aircraft engine combustors while progressively strengthening capacity. Combustors are one of the hottest engine components, which require a certain level of combustion stability, durability, emission, and other characteristics that conflict with each other in some cases. For next-generation civil aircraft engines, improvement in environmental compatibility without compromising durability, even as the load on high-temperature components increases is needed in order to increase fuel efficiency. To address this, the manufacturing division, design division, and Research & Innovation Center are collaborating to develop technologies unique to the Mitsubishi Heavy Industries Group.

Methods to enhance combustor durability include, first, improving cooling hole quality and introducing hole shapes with higher cooling performance. For example, abrasive waterjet processing technology, which applies less heat to components during processing, is being employed. In addition, solutions for difficult challenges are sought based on knowledge acquired through the development of high-speed laser processing technology. Laser processing and abrasive waterjet processing are illustrated in **Figure 7**. Also for the laser processing, efforts are underway to create further added value by utilizing advancements in laser oscillators, such as ultra-short pulses and high peak power.

Thermal barrier coating (TBC) is another key technological element that significantly affects durability. However, electron-beam physical vapor deposition (hereinafter referred to as EB-PVD), used on ultra-high-temperature components like turbines, has limitations in terms of suppliers and lead time of mass production launch due to special characteristics of its equipment and process. On the other hand, development of suspension-high velocity oxy fuel (hereinafter referred to as S-HVOF) shown in **Figure 8** and suspension plasma spray (SPS) is underway with the ambitious goals of achieving thermal barrier properties, thermal cycle life properties, and erosion resistance equal to or exceeding those of EB-PVD, while enabling mass production launch within a shorter time frame and with simpler equipment.

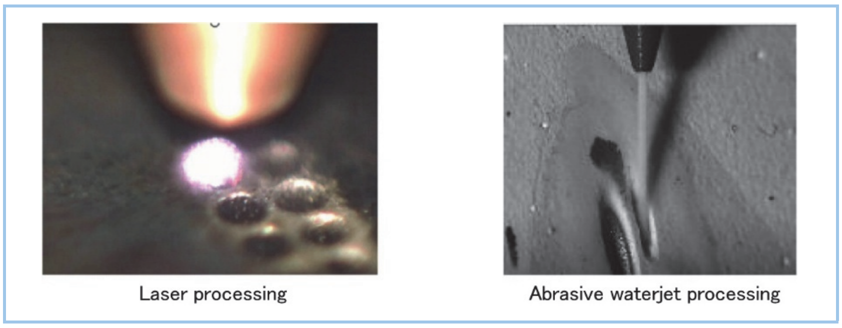

Figure 7 Cooling hole processing technology

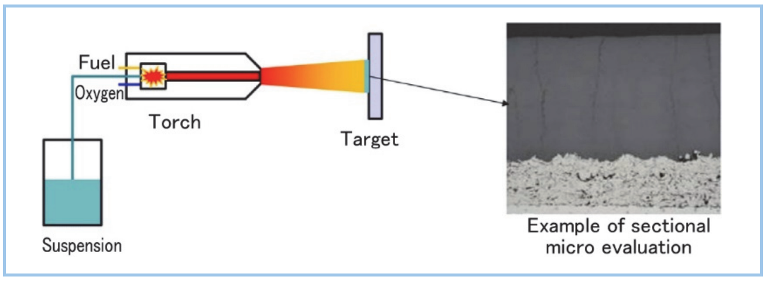

Figure 8 Schematic diagram of S-HVOF

4. Conclusion

This report presents activities by MHIAEL to enhance development capabilities for next-generation civil aircraft engines. The following efforts for LPT have been taken:

- Aerodynamic design technology: The advantages of front-loaded airfoils were verified through linear cascade tests, and their characteristics were demonstrated under multi-stage and rotating conditions through rotating tests, and low-loss blade design technology was established.

- Seal technology for leakage flow reduction: Characteristics of mainstream flow gas leakage were obtained through verification tests of the rim seal structure, and prediction accuracy of secondary air volume which significantly affect LPT efficiency was improved.
- Blade vibration control technology: Effectiveness of the damping mechanism was confirmed through rotational vibration tests of the rotor blade, and vibration design technology for high-aspect-ratio LPT rotor blades was established.
- Technology demonstration using actual engine testing: Verification of system feasibility was carried out using an actual engine, and data regarding performance, secondary air, and vibration was acquired from more than 1,000 measurement points, thus improving various prediction technologies.

Furthermore, regarding the manufacture of combustors, technologies unique to the Mitsubishi Heavy Industries Group continue to be developed, such as waterjet processing and low-heat-input advanced laser processing to improve durability of cooling holes, as well as advanced alternative coating technologies to improve mass-production feasibility, with the goal of creating products that balance durability and environmental compatibility.

To achieve the 2050 carbon neutrality goals agreed upon by IATA and ICAO, development of more efficient airframes and propulsion systems by aircraft and engine manufacturers is needed.

MHIAEL will also continue to develop technology related to LPT and combustors, which are strategic-area components. For LPT aerodynamic design technology, further designing and implementation of rotating testing of a prototype, to achieve improved high-pressure ratios and higher efficiency are planned in order to enhance technological maturity. Regarding combustors, technologies that highly balance durability and environmental adaptability will be actively pursued.

Through these activities, MHIAEL seeks to apply its technologies in next-generation civil aircraft engines and further strengthen its technological contributions to engine development programs.

References

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(2) Forced Response Variation Evaluation of Low-pressure Turbine Blade in Aero Engine Test, IGTC 2023