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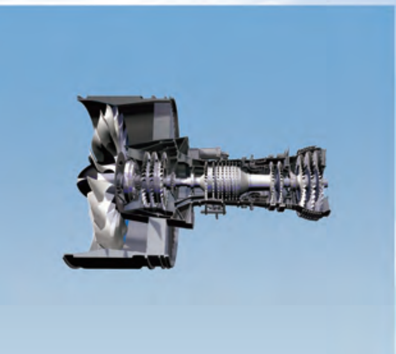
KAWASAKI TECHNICAL REVIEW

Special Issue on Aerospace Systems



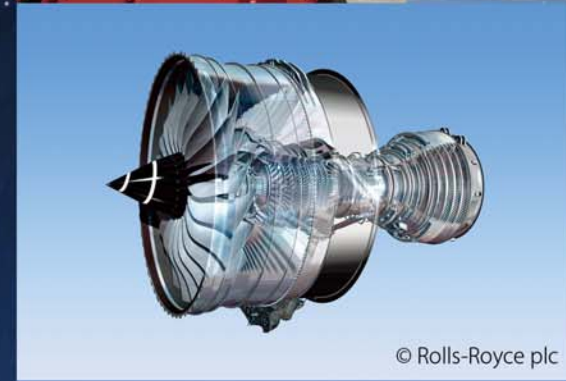


TECHNICAL REVIEW

No.179
October 2018

Kawasaki Heavy Industries, Ltd.

Integrating state-of-the-art technologies to soar into the sky and beyond.



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The Present Situation of the Aerospace Systems Business and its Development Going Forward

Sukeyuki Namiki
Director, Managing Executive Officer
President, Aerospace Systems Company

Please tell us about how Aerospace Systems Company came about.

In April 2018, the former Aerospace Company was merged with the Gas Turbine Division's Aircraft Engine Section and reincarnated as an organization that handles a comprehensive range of aerospace systems, including engines.

The rationale behind this integration was to allocate key management resources to a growing field in the market. Our objective is to strengthen our business by improving the way we harness synergy; that is, to enhance our technological prowess through the fusion of our airframe and engine system integration technologies, to expand cooperation across different projects, to improve production capacity through the expansion of our production bases. The company is organized in a fashion that places business entities that handle common product lines as the project headquarters. This effectively makes them organizationally independent and clearly defines their responsibilities, giving them the ability to carry out each strategy faster than ever before.

How is the aerospace systems business at present?

Allow me to introduce the three core pillars of our business: defense aircraft, commercial aircraft, and aircraft engines.

In terms of the defense aircraft business, we have completed the development projects for both the P-1 Maritime Patrol Aircraft (P-1) and the C-2 Cargo Aircraft (C-2), and are now in the mass-production stage. Plans are to deliver five P-1 aircraft per year starting in FY2018, and three C-2 aircraft in FY2018. In addition, the Three Principles on Transfer of Defense Equipment and Technology, which authorizes the export of defense equipment under certain conditions, was formulated in 2014. In relation to the equipment that we might export under this government policy, we held exhibits for the P-1 in Paris, and the C-2 in Dubai last year at international airshows. Both models attracted plenty of attention from countries across the globe.

As for the commercial aircraft business, in the midst of growing global demand, our manufacturing of major airframe component for Boeing has been booming. For example, we have been producing the forward fuselage for the Boeing 787 (787), manufacturing 14 units per month at the Nagoya Works. Regarding the Boeing 777X, the successor to the Boeing 777, we began operations at the new plant at the Nagoya Works, as well as at KMM's Lincoln manufacturing site, the US local subsidiary, in May 2017. We began shipments in February the following year. The manufacturing facilities we have been using for these projects leverage a wide range of new technologies, such as robotics to automate and accelerate production and to stabilize quality.

Regarding aircraft engines, our focus is on promoting the businesses dealing with three modules: intermediate pressure compressors, gears, and combustors. We've reached a peak in our development of compressors for the Trent series of large turbofan engines for Rolls-Royce, and mass shipments are increasing sharply. What's more, we're in charge of developing and manufacturing combustors for Pratt & Whitney's PW1500G engines. This has been a success, and mass shipments started in 2017.

Please tell us about the future prospects of the aerospace systems business.

As far as the defense aircraft industry is concerned, we're exploring opportunities to modernize and expand into derivative airplanes while steadily continuing to mass-produce the P-1 and C-2 models. In addition, the company is venturing into new projects and expanding our market share by leveraging our system-integration capabilities cultivated through many years as an aircraft manufacturer. Another aim is to expand businesses related to repairs and supply.

Primary objectives for the commercial aircraft industry are to improve productivity and to refine our organizational structure by promoting future business growth. In order to achieve these objectives, we maintain our world-class technological strength, which is propelled through international joint development with Boeing, and hone our competitive advantages, which remain beyond the reach of emerging nations due to our high production capacity and standards of quality achieved with our state-of-the-art equipment and the technology of Internet of Things (IoT).

Looking at the aircraft engine industry, we will continue to build on our engineering capabilities as a module supplier, and establish our position as a module integrator capable of everything from baseline design and beyond. Another focal point will be to secure revenue by expanding the aftermarket business. Ultimately, our goal is to develop and deliver engines under our own brand name.

Closing comments

Now that our major development projects for the P-1, C-2, and 787 are bearing fruit, we've entered a stage where we must look to the future to embrace the challenges that various new enterprises in both defense and commercial aviation present. The focus on development continues unabated in parallel with the steady growth of our existing businesses.

Kawasaki Takes Aerospace System Product and Technology to New Heights

Naoki Kodama
Associate Officer
General Manager, Engineering Division, Aerospace Systems Company

Introduction

Established in 1919, the aircraft division of Kawasaki has developed in both the military and civil fields in line with the progress of aircraft and it has expanded into the defense system and space fields.

As the Aerospace Systems Company has recently moved the defense aircraft section into mass production stage of developed models, business is expected to continue to be stable. In the commercial aircraft business, much growth is expected because of a medium- and long-term global increase in passengers and cargo volume as a result of economic growth in emerging countries. Under these circumstances, we are pursuing further development by venturing into new business fields in addition to those extended from existing businesses.

1 Features of the Aerospace Systems Company

The Aerospace Systems Company is involved in a wide range of aerospace-related businesses with the objective of being an internationally competitive aircraft manufacturer in terms of quality, cost, and lead time as a leading company in the aerospace industry in Japan. We also continuously strengthen our technological capabilities highly appreciated by customers and the market and further improve the quality, cost and speed of our services to succeed in the midst of great international competition.

We restructured the organization in April 2018 as an aerospace system manufacturer that deals in aero engines in addition to aircraft, defense systems, spacecraft and other products. We aim to be an aircraft manufacturer that has a greater ability to integrate systems by merging the technologies and know-how we have on airframes and engines, and provide new values to the industry.

2 Overview of major products in each business field

(1) Military airplanes

We have played a major role in developing and manufacturing a variety of models including the T-4 intermediate trainer and the P-3C patrol aircraft. As the prime contractor of the development project of the first large aircraft made in Japan in 30 years, we completed development of the P-1 maritime patrol aircraft and the C-2 transport aircraft and are now engaged in manufacturing their production aircraft.

The P-1 is a rare aircraft that has an all new airframe, engine and avionics equipment specifically designed for maritime patrol missions. The P-1 can be used at low and high altitudes and speeds through the application of new technologies including the world's first operational fly-by-light control. After completing its development in FY2012, we have been delivering production aircraft to the Japan Maritime Self-Defense Force, where they will be used to ensure maritime security around Japan in place of the P-3C airplane.

The C-2 is the largest aircraft ever developed in Japan. The C-2's maximum take-off weight is about three times heavier than that of the C-1 and the C-2 can transport people, vehicles, pallet cargo and many other different forms of cargo with the latest load management system. After completing its development in FY2016, we have been delivering production aircraft to the Japan Air Self-Defense Force, where they will be used in air transit missions in international peace cooperation and other activities in place of the C-1 airplane.

We will continue to stably mass produce these two large aircraft as our leading products, while aiming to improve their capabilities and apply them to the derivative airplane business. Both of these models have drawn international attention through activities such as a ground exhibition of the P-1 (**Fig. 1**) at the Paris Air Show in June 2017 and that of the C-2 (**Fig. 2**) at the Dubai Airshow in November 2017.

Fig. 1 Overseas ground exhibition of the P-1 patrol aircraft

Fig. 2 Overseas ground exhibition of the C-2 transport aircraft

The T-4 intermediate trainer (**Fig. 3**), which Kawasaki developed as the prime contractor, has been actively used by the Blue Impulse team. However, it has already been more than 30 years since it was developed. We will promote project proposal activities to modernize the mounted systems and develop its successor.

Fig. 3 T-4 intermediate trainer

(2) Commercial airplanes

In the commercial airplane field, we have contributed to the international joint development programs for Boeing's wide-body aircraft, the Boeing 767, Boeing 777, and Boeing 787, in the U.S. and Embraer's regional aircraft, the E170 and E190, in Brazil by leveraging all of our engineering capabilities as an aircraft integrator, all the while accumulating technologies as we participated in these programs. In particular, the 787 (**Fig. 4**) is an innovative passenger aircraft that has used carbon fiber composite materials in place of conventional metals wherever possible. We have sophisticated technologies to design and manufacture the sections we are responsible for through joint development and have established our position as one of the foremost composite body

Fig. 4 Boeing 787 series

manufacturers in the world. The Boeing 787 family includes the Boeing 787-9 and Boeing 787-10 as derivative airplanes with extended bodies in addition to the basic Boeing 787-8 model.

We are now participating in the development of the successor of the 777, the Boeing 777X. The 777X (**Fig. 5**) is a next-generation aircraft wholly renovated to realize passenger comfort similar to the 787 by introducing new technologies applied to the 787 though it is a derivative airplane of the 777, whose body is made of metal. While the basic Boeing 777-9 production has been started toward delivery in 2020, the development of a short-body derivative airplane for ultra-long range flight, the Boeing 777-8, is also underway.

When manufacturing the 787, we succeeded in producing innovative composite material structures for 14 aircraft a month, an unprecedentedly high rate of production, through advanced automation such as automated placement of composite materials. We also internally developed the latest robot system and constructed and started operating a new factory to further promote automation in the manufacture of the 777X. In addition to high quality and efficient production through integration with a production method that we created during the production of conventional models to improve efficiency known as the Kawasaki Production System (KPS), we are preparing the infrastructure to shift to smart factories that include ICT and IoT in the future.

Through these efforts, we will further enhance international competitiveness in terms of quality, cost and lead time and attempt to participate in new projects such as international joint development of future commercial aircraft.

Fig. 5 Boeing 777X

(3) Helicopters

We have built up a solid technological foundation and internally made advancements in our research to develop our own helicopters since we first began producing and repairing helicopters under a license agreement that began shortly after the end of World War II. So far, we have developed the BK117 with Airbus Helicopters in Germany in an international joint project in the civil sector and the OH-1 observation helicopter for the Japan Ground Self-Defense Force in the defense sector.

The main feature of the OH-1 is its high maneuverability enabled by components such as a composite rotor hub. As it has been more than 20 years since its maiden flight, we are moving forward with research and proposal activities that include modernization of its electronic devices to enhance mission capabilities.

The CH-47 large transport helicopter (**Fig. 6**) operated by the Japan Ground Self-Defense Force and the Japan Air Self-Defense Force is actively used for purposes including disaster relief and international emergency assistance activities such as transport of supplies/people and aerial firefighting. We have continued to manufacture the CH-47, enhancing capabilities according to the mission based on a license agreement with Boeing.

The MCH-101 minesweeping and transport helicopter used by the Japan Maritime Self-Defense Force was manufactured by equipping Leonardo Helicopters' AW101, jointly developed by Italy and the U.K. and manufactured under a license agreement, with our proprietary minesweeping system and other systems. A CH-101 multi-purpose helicopter, which is akin to the MCH-101, is loaded onto the icebreaker Shirase that operates in the Antarctic waters, to transport supplies and support the research expedition team.

In the defense helicopter business, we are offering derivative models for new missions. We have also started entering into comprehensive logistics support agreements including inventory guarantee of supplies based on analyses and forecasts from past operation records and guarantee of the availability ratio to support efficient operation.

The BK117 commercial helicopter is the best-selling model with sales of more than 1,400 units around the world since the acquisition of a type certification in 1982. Operated by private companies, municipalities, or other organizations, the BK117 is actively used in a wide range of fields including people transport, firefighting, rescue, police, emergency medical service, and media and it has earned a great reputation. We have also continued to develop derivative models and launched the latest model, the H145//BK117 D-2 (**Fig. 7**) in 2016. We are developing new technologies including research on safety enhancement in rescue missions under severe conditions as Japan's only manufacturer and supplier of commercial helicopters.

(4) Defense systems

We have developed all the anti-tank and anti-landing craft missiles in Japan. The latest Medium range Multi-Purpose missile was developed as the successor of the Type 79 anti-craft and anti-tank missile and Type 87 anti-tank missile and is now mass-produced and delivered to the Japan Ground Self-Defense Force. We introduced the latest technologies including target detection using information from infrared images and millimeter radar in this missile. Furthermore, we fulfilled our contract with the MOD for a prototype of a future network-capable multi-purpose missile system in FY2012 and have accumulated expertise such as infrared target identification technology that uses artificial intelligence (AI) and the networking technology to realize the optimal system operation leveraging network information.

We have also developed the Small & Smart Target Drone System by applying the guidance and control

Source: Ministry of Defense (MOD)

Fig. 6 CH-47 large transport helicopter during firefighting

Fig. 7 H145//BK117 D-2

† Realized the world lowest level of noise in its class, better hovering performance and longer lifetime through adoption of a new tail rotor and other components.

technologies that we gained by developing missiles. This target drone is employed as the air-launched small aerial target for fighter jet training by the Japan Air Self-Defense Force and has contributed to an increase in training opportunities by reducing the cost to about one-fourth of the conventional one. In addition, we have altered this drone to support anti-aircraft firing training by the Japan Ground Self-Defense Force and plan to start delivery in FY2018. This target drone uses the KJ14, a highly versatile small turbo jet engine developed by Kawasaki. We are also actively making proposals for derivative models for further expansion of its applications.

In addition, we are developing high power laser systems, as we consider them to be an innovative technology that could be a game changer in future defense missions. We have researched and developed defense applications based on iodine laser technology which was developed for industrial purposes over a long period of time. Now, we are developing a fiber laser system (**Fig. 8**) that allows for size reduction, instantaneous response, and lower cost in preparation for equipping the air defense system with it in the future.

(5) Space

We have contributed to space development in Japan in many different fields including rockets and space stations. We are Japan's only developer and manufacturer of fairings, which store and protect satellites in the tips of rockets, and we are currently building the fairings for rockets including the H-IIA/H-IIB, Epsilon, and the H3, whose first model is scheduled to be launched in 2020. For Japanese Experiment Module, named "Kibo" on the International Space Station, we developed and manufactured key parts such as the airlock that divides the pressurized section where astronauts stay from the vacuum of space. Airlocks are frequently used for purposes such as receiving supplies, recovering specimens after experiments have been conducted outside the station and deploying small satellites. We are now focusing mainly on research and development toward realization of a satellite that removes space debris (**Fig. 9**) as there is a lot of it adrift in orbit and it could collide with satellites or space stations. We are also stepping up efforts in related businesses and in developing many different satellite subsystems.

(6) Aero engines

(i) Aircraft engines

The beginning of our aircraft engine business was the development of the "Ne" series engine during the war, and during Japan's postwar years, we started overhauling engines made by Western manufacturers in U.S. military aircraft. We now manufacture and overhaul many aircraft engines such as the T53 engine for the UH-1 and AH-1 helicopters, the T55 for the CH-47, and the RTM322 for the MCH-101 and CH-101, all of which are used by the Self-Defense Forces. We have also participated in the design and manufacture of parts in the five-country joint development project of the V2500 engine for the Airbus A320, which started in the 1980s.

We enjoy a close collaborative relationship with Rolls-Royce headquartered in the U.K., one of the world leading aircraft engine manufacturers for large commercial aircraft. The bond of our strong friendship has been nurtured since 2004, when we were given our first opportunity to manage all the processes from design to assembly of the Intermediate Pressure Compressor (IPC), one of the major modules used in the Trent 1000 engine for the Boeing 787. Since then, we have been in charge of the IPC module in the development of the Trent XWB engine for the Airbus A350 XWB and the Trent 7000 engine for the Airbus A330 neo and have shipped more than 1,000 modules so far.

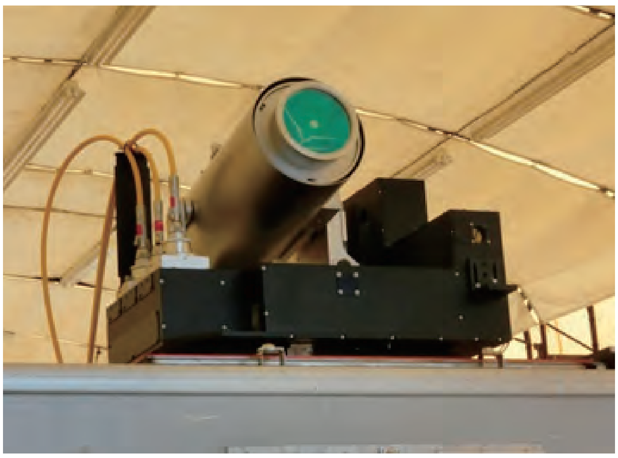


Fig. 8 High power laser system (fiber laser system)

Fig. 9 Debris removal satellite

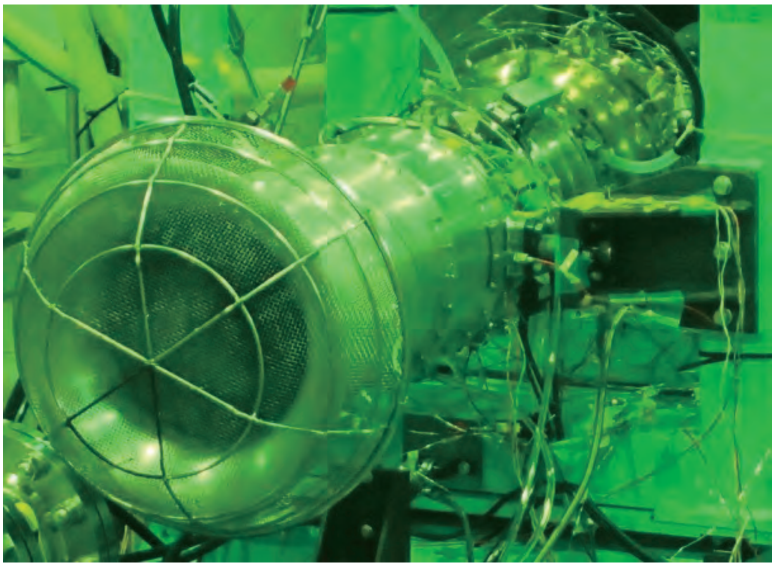


Fig. 10 KJ100 engine under test

We have been developing technologies for low NOx combustors for a long time as one of our proprietary technologies while addressing environmental regulations that get stricter year by year. Currently, we are developing technologies for the next-generation of engines for medium-size commercial aircraft.

In addition to the KJ14, which is mounted in the autonomous small target drone for the Japan Air Self Defense Force and the Japan Ground Self-Defense Force, we are also developing engines such as the KJ100 (**Fig. 10**) under the concept of small size and high power, aiming for their use in aircraft including future high-speed target drones.

(ii) Aircraft gearboxes

We develop, manufacture, repair and overhaul aircraft gearboxes including transmissions for helicopters, accessory gearboxes for aero engines, and the T-IDG (Traction Drive Integrated Drive Generator) for aircraft, which was developed by incorporating the Traction Drive CVT (Continuously Variable Transmission) into our product. We have also started developing technologies for gearboxes for next-generation aircraft and manufacturing fan drive gear systems for aircraft engines.

3 Technology development

(1) Artificial intelligence (AI) technology

Not only do we focus on airframe-related technologies but also on the mission avionics technology accumulated through the experience it gained in projects such as the development of the P-1. We have also fulfilled our contract with the MOD for a prototype tactical decision support system using AI technology (**Fig. 11**), which supports decision making of commanding officers in flight. This system is expected to prove very effective during operations. We regard this technology as the core technology of future modernization and derivative model businesses and are always looking for ways to use it in the many businesses of the future we are engaged in such as mission planning and operation control of autonomous unmanned aerial vehicles. In addition, we are conducting research on standardizing application software to make it operable in different computer environments with the aim of accelerating technology deployment.

AI is becoming increasingly practical and is being applied in a variety of industrial fields at an accelerating pace. We are also conducting research on decision making, action planning, and evaluation in addition to

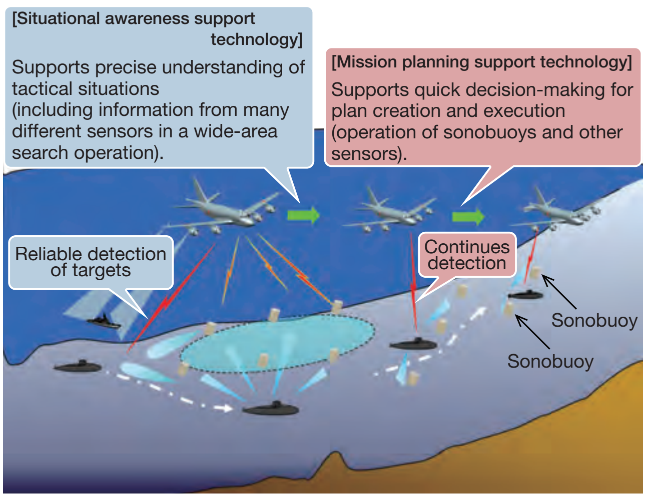


Fig. 11 Overview of tactical decision support technology

detection of signs of failure from information such as data accumulated during the development and operation of aircraft, and are considering application and development for future products such as crew support and expansion of the autonomous range of aircraft.

(2) Aircraft-related simulator technology

We can verify the system design before actual flight by having internal and external pilots evaluate the flight characteristics, visibility of instruments, operability of devices and other factors using our simulator for research and development during the development of new aircraft or internal research. The simulator exhaustively models the external environment including atmospheric conditions in addition to the movement of the aircraft and precisely simulates cockpit equipment including displays, control elements and instruments. This makes it possible to review designs through pilot evaluation and locate system defects at an early stage.

We have also developed pilot training simulators and maintenance training simulators for the aircraft such as the P-1, C-2, and MCH-101 based on the simulator technology we have accumulated so far by adding simulation elements in the real world such as the fuselage system, field of view, acoustics and vibration and delivered them as products, contributing to improvement in the efficiency and effectiveness of customers' training.

In addition, we are researching advanced simulator technology in which actual aircraft and multiple simulators are linked to realize training for complex missions where aircraft, ships and other vehicles interact with one another for product development in the future.

(3) Aircraft systems technology

Regarding aircraft systems technologies, we are conducting research and development on sophistication of system development on a more advanced level including model-based development that improves development efficiency and design quality, and high efficiency systems such as power and thermal management to address energy saving and cost reduction that is under way on a global scale to acquire foundational technologies for the realization of future aircraft. We are also conducting many different research projects on mission-related systems that are able to support an increase in applications of transport or other aircraft and instrumentation-related systems and network-type telemetry communication that supports next-generation aircraft and space equipment in the light of domestic and overseas situations.

(4) Technologies related to compressors, combustors and gears in aero engines

We are responsible for the design of an increasingly large number of parts as a result of its long-time collaboration with Rolls-Royce and striving to enhance our technological capabilities in order to become a “module integrator” that designs and develops compressors by ourselves in the future.

We are researching the application of ceramic matrix composites (CMC) to combustors in a NEDO project. CMCs are expected to be used in aero engines as a light, heat-resistant composite material. We will attempt to participate in new engine projects based on these technologies.

We also made it a goal to start a maintenance, repair & overhaul (MRO) service for commercial engines as a business within the next few years and to be an original equipment manufacturer (OEM) of manned aircraft engines in the future. To achieve this goal, we are constructing a strong technological foundation and organizational structure.

In the future, the demand for aircraft gearboxes will increase in line with the growth of the aircraft market and the market for high-capacity generators will increase as a result of the electrification of aircraft. However, only a handful of suppliers have advanced design and manufacturing technologies or have experience developing and manufacturing aircraft gearboxes. Considering such circumstances, we will continue our research and development to further improve our products in terms of their functionality and performance, pursuing our goal to become one of the top aircraft gearbox manufacturers in the world.

(5) Composite material-related technology

With excellent characteristics, namely, lightness, high strength, high rigidity and high corrosion resistance, carbon fiber composite materials have been increasingly applied in the aerospace field at a fast pace. Typical examples include commercial passenger aircraft such as the 787. We started development of materials that can be applied to commercial aircraft from early on and developed a material known as KMS-6115, according to our own standards. KMS-6115 was approved by the aviation bureaus in Japan and overseas in 1999 and was used in the BK117 as well as the P-1 and the C-2.

We also developed KMS-6125 through joint research with a material manufacturer in 2017 to meet the recent demand for low-cost high-rate production. This material has two remarkable features. The first is low-pressure formability that realizes good characteristics only using an oven and vacuum pump without having to use the expensive pressurizing and heating facilities required for conventional composite materials. The second feature is an excellent laminating characteristic realized by the automated placer (**Fig. 12**). KMS-6125 is highly expected

Fig. 12 Automated placement of the carbon fiber composite material KMS-6125 prepreg

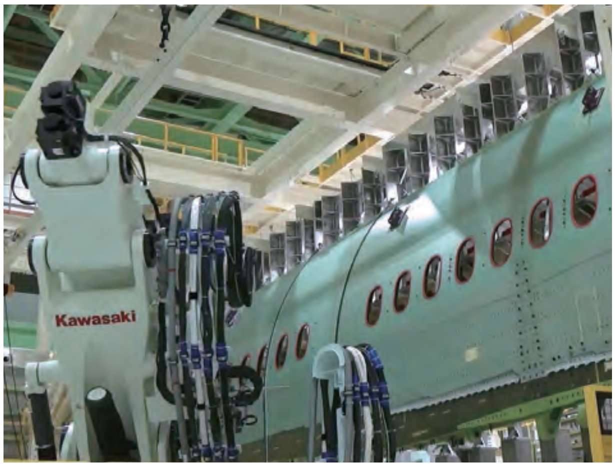


Fig. 13 Large-diameter boring robot system

to contribute to cost reduction in the future through applications in space equipment, airplanes and other products.

Regarding manufacturing technology, we are developing the automation and precision improvement technologies for parts with complex shapes assuming use in the fuselage structure of airplanes and rotorcraft and we are strengthening its overall competitiveness by focusing on low cost and stable quality.

On the other hand, composite materials tend to suffer more damage than metal in a lightning strike and therefore require critical lightning protection design. For this reason, we have been developing an analysis method to predict the damage that would occur in the event of a lightning strike with JAXA since 2012. We are also making lightning damage analysis more sophisticated. Measuring the temperature and distortion inside the composite materials using fiber optic sensors and taking photos with an ultrahigh-speed camera allows us to clarify how composite materials are damaged by a lightning strike.

(6) Manufacturing technology

To strengthen competitiveness to win new contracts and improve profits in each type of project, we are developing manufacturing technologies that lead to reduced costs and improved efficiency.

We are developing assembly technologies to reduce labor cost and lead time. We have completed development of the processing accuracy and large-diameter drilling technologies for drill robots and applied them to the manufacture of the 777X (**Fig. 13**). We are also developing automatic fasteners and sealers using robots.

We have continued to develop the technologies for sheet metal to reduce assembly costs and weight through structure integration with friction spot joining (FSJ) and friction stir welding (FSW). Although part accuracy has been a challenge for sheet metal forming, we are in the process of automating chip forming and roll forming, and improving the forming accuracy, aiming for accuracy equivalent to that of machine processing.

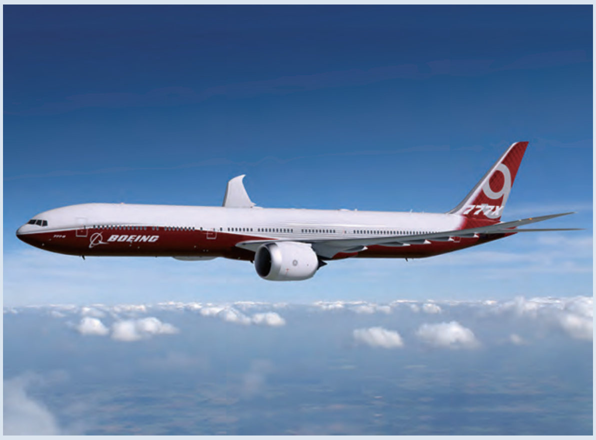
In the machine processing field, we are developing a cutting technology suited to the vibration characteristics of machine tools rather than only depending on the introduction of state-of-the-art machine tools and are thus improving the processes in an integrated way. For shorter lead times, we are also developing cutting tools for composite materials while developing low-cost setup robots.

Given the recent application of IoT to production, we are also innovating production using the IoT. For example, we are considering traceability automation by an identification system that uses RFID (Radio Frequency IDentification) tags. In order to achieve this objective, we are conducting field tests for individual identification.

Conclusion

To improve our international position as an aerospace-related company, Kawasaki encourages commitments such as further expansion of market share, promotion of international joint development and manufacture projects and strengthening of product proposals with new concepts all centered around our core businesses. We will also focus on advancing foundational technologies including materials, design, evaluation, production, and operation support as the source of the international competitiveness required for them. On top of that, we will step up to the challenge of conducting research and development of technologies for labor saving, energy efficiency improvement, system integration, safety guarantee, reduction in environment loads and other areas needing further development to provide new values through such development.

State-of-the-Art Large Commercial Aircraft Boeing 777X



As the number of jetliners is expected to steadily increase, the demand for the Boeing 777X, the successor to the Boeing 777, is expected mainly in crowded and long-distance airline routes. Boeing launched the 777X development program in November 2013 and plans to bring it into service in 2020.

We have participated in this joint international development from an early stage of design and worked on cost reduction and automation, for example, by deploying an automated design tool or enhancing the application range of assembly robots.

Introduction

According to a long-term forecast for commercial aircraft demand, the number of passenger jets in operation is expected to steadily increase because of a 4.6% annual average growth rate of revenue passenger kilometers over the next 20 years[1].

1 Background

The Boeing 777 is a best-selling twin-engine passenger jet realized by the international joint development of which was participated in by Kawasaki in the 1990s. It is expected that there will be demand for it mainly on busy passenger routes and long-distance routes under the current airport congestion and long-term increase in fuel prices. The Boeing 777X development program was launched in November 2013 as the successor to the Boeing 777 with the aim of further improving selling power and competitiveness.

2 Development Plan

For the international joint development of the 777X, Kawasaki took charge of the same production workpackage as the Boeing 777 as shown in **Fig. 1**.

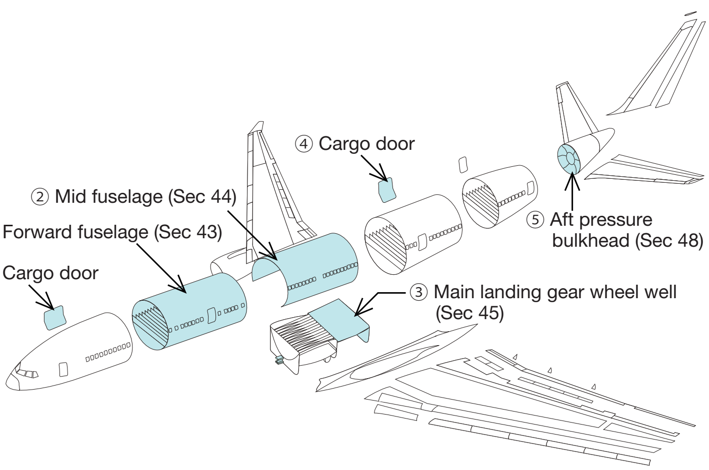


Fig. 1 Production workpackage in Boeing 777X

Before this aircraft development, we carried out technology development of materials, structures and manufacturing engineering for the main parts of the fuselage structures starting in 2013 in order to realize advanced aluminum fuselage structures under joint development with Boeing. This technology development is reflected in the actual production equipment and facilities. In the fuselage development, as is the case with the development of derivative airplanes of the 777, we also participated in airplane level work (known as program level work) in addition to design and analysis works as a member of the development team formed in the Boeing Company in the U.S. From September 2015 through June 2017, about 30 engineers took part in the joint development.

According to the initial plan, all design activity would be completed in the U.S. But, to improve manufacturability and design data quality, it was decided to design in Japan simultaneously, so a design team of about 30 members was formed. Designing it in Japan contributed to the overall development schedule and was highly evaluated by the Boeing Company because of the high-level communication and engineering capability that capitalized on the experience accumulated in past joint development projects.

3 Outline of the Aircraft

There are two types of the 777X. One is the Boeing 777-9 that has more passenger seats, and the other is the Boeing 777-8 that has the longer cruising range. The Boeing Company received the first order from Lufthansa German Airlines and then launched the development of the 777-9.

(1) Major Specifications

The 777-9 has a stretched fuselage as a derivative of the present Boeing 777-300ER. It has more than 400 passenger seats and its cruising range is 14,075 kilometers (7,600 nautical miles). Its wing structure is made of composite materials instead of the conventional aluminum alloy to improve aerodynamic performance. While the wing span is extended, it has folding wing tips so that it does not exceed the limit set by airports. It is powered by General Electric's new engines and its fuel efficiency 20% better than the present model. A comparison of the major specifications is shown in **Table 1**. As shown in **Fig. 2**, the latest interior designs such as LED lights, large cabin windows and humidifying devices are applied.

Table 1 Specifications of the 777-9 and the 777-300ER

Aircraft Model	777-9	777-300ER
Seats	414	396
Design Range〔km (nm)〕	14,075 (7,600)	13,649 (7,370)
Overall Length〔m〕	76.7	73.9
Wingspan〔m〕	71.8 (64.8 on ground)	64.8
Overall Height〔m〕	19.5	18.5
Engine	GE9X	GE90-115BL

Table 2 Major structure of workpackage (forward and mid fuselages) in the 777-9 and the 777-300ER

Aircraft Model	777-9	777-300ER
Passenger entry door location	Center of forward fuselage	Front of forward fuselage
Standard layout of passenger seats	10-across seating	9-across seating
Cabin pressure〔kPa (psi)〕	62 (9.0)	59 (8.6)
Cabin window height〔mm (in)〕	441 (17.36)	390 (15.36)
Fuselage skin material	AL2524 / AL2029	AL2524 / AL2024

(2) Change in Primary Structure of the Workpackage

In the case of the 777-9, as shown in **Fig. 3**, as the stretched part of the forward fuselage is located on the nose side of the forward fuselage (Sec 43), the position of the passenger entry doors are not all closer to the front unlike the present model. As the position of passenger entry doors are located closer to passengers in the central part of the fuselage, the emergency exits[2] in the mid fuselage (Sec 44) were removed to reduce weight and cost.

For the seat configuration, the cabin width was increased to make 10-across seating the standard, and the side frame height was reduced by 42 mm (1.65 inches) at maximum on the broadside by changing the side frames of the cabin from sheet metal to machined integral parts.

Moreover, the cabin environment is improved in the same way as for the 787 by improving the cabin pressure and making the cabin windows bigger. Also, the reliability and maintainability were improved by applying a corrosion-resistant material (AL2029) to part of the lower skins of the fuselage. A comparison of the major structures of the forward and mid fuselages, which made up our workpackage, is shown in **Table 2**.

4 Challenges in 777X Design and Production

(1) Design

To improve marketing competitiveness, the 777X required redesign of almost all of its major structural parts to optimize the cost and weight, in addition to design changes due to changes in specifications, while its fuselage structure followed the basic structural type of the present model. Therefore, within the limited schedule and budget, it was required to create many models and drawings. Moreover, to expand the scope of application of automation, it was necessary to ensure tool clearance and reflect the specifications of production equipment such as robots and machine tools in the design at an early stage.

Fig. 2 Interior image of the 777X

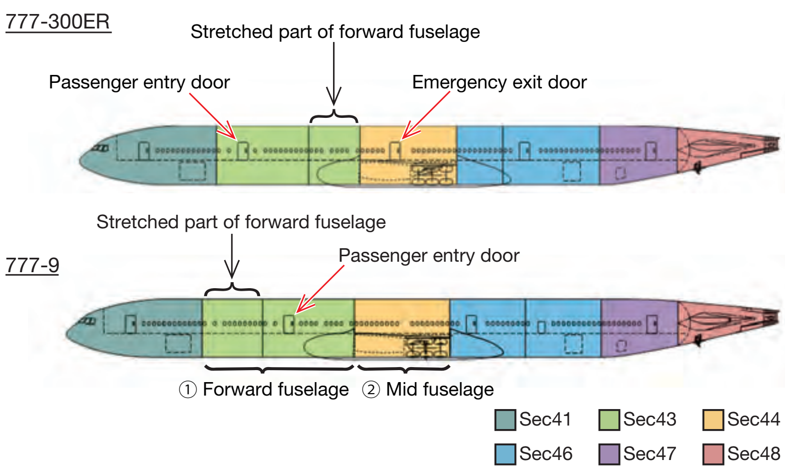


Fig. 3 Overview of change to the fuselage extension

(2) Production

In the production of the 777X, it was necessary to increase the level of precision for final assembly by the Boeing Company and for side frame integration.

(i) Final Assembly by the Boeing Company

As shown in **Fig. 4**, the Boeing Company decided to make changes by introducing a jig-less assembly method that makes full use of robots into the final assembly line of the fuselage. With this decision, the conventional jig-and-tool-based method was changed to a method that uses coordination holes drilled in the panels of our workpackage. If the precision of these coordination holes was poor, the fuselage would not be able to be assembled as designed in the final assembly process by Boeing, which would cause much adjustment work. As poor precision would be a hindrance to planned production, it was necessary to increase the precision of the coordination holes of the panels.

(ii) Side Frame Integration

As shown in **Fig. 5 (a)**, as the present 777-300ER has a structural type in which the side frame parts made of sheet metal are attached to the fuselage skins using shear ties as structural members, the unevenness of the frames and skins themselves can be compensated for by the shear ties. As shown in **Fig. 5 (b)**, on the other hand, the 777X uses machined integral parts, including shear ties, and its structure has been changed to directly fasten side frames to fuselage skins. Therefore, it was necessary to increase precision because of the possibility of significantly increasing the work of fill gaps in the assembly process. Moreover, aiming at further increasing the efficiency of productivity, we decided to expand the scope of automation, not only by making use of conventional assembly equipment but also by developing robots.

Fig. 4 Final assembly using robots (at Boeing)

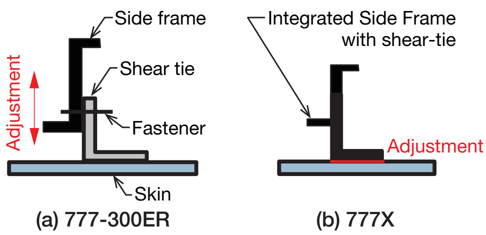


Fig. 5 Integrated side frame

5 Efforts

(1) Design

To improve the efficiency of the design work, automated design tools that use the relational design and programming functions of CATIA V5 CAD software were applied to major structures of the fuselage. Relational design is a function of CAD software that automatically adjusts 3D shapes when the dimension values of parts are changed. 3D models of parts and some of the 2D drawings were both automatically created based on the 3D models using this function. Automated design tools can also be used to decide on shapes and fastener locations of parts by considering design requirements, materials to be applied and production equipment in advance. This has made it possible to design many parts of consistent quality with a small number of people in a short period of time.

The decrease in strength due to burrs and elastic seals that are caused at the time of drilling cannot be accepted in some cases at the fastener joints where faying surface seals are applied between parts for airtightness and corrosion resistance. In such cases, we coordinated with the production and technology division and specified detailed production information such as drilling methods, the sequence of fastener installation and clamping methods/locations in production drawings and process control drawings.

(2) Production

(i) Increase in Precision

As part of our efforts to increase precision, we made temperature control during part processing stricter. In the past, we compensated for the operation programs of production equipment in response to the temperature environment immediately before processing. But, as temperature changes cannot be accounted for when processing is in progress, it sometimes caused a slight difference in the precision of parts between the highest and lowest temperatures during daylong processing. In the case of the 777X, it was made possible to carry out processing at the specified design temperature by eliminating disturbances due to temperature correction in the machining of side frames as large structural members, assembly work of 10-meter or longer fuselage skin panels and the sub-assembly work of stringers. For the fuselage skin panels, we produced skin retainers equipped with the high-precision actuators shown in **Fig. 6** for processing as designed and realized high precision drilling of coordination holes.

In addition to measures for increasing the precision of parts, the final assembly of panels was changed from conventional vertical installation as shown in **Fig. 7 (a)** to horizontal installation as shown in **Fig. 7 (b)**, and the inner surface of the fuselage skin panel was followed evenly in a stable manner to the jig and tool standards, making it possible to construct the inner surface of the panel as designed.

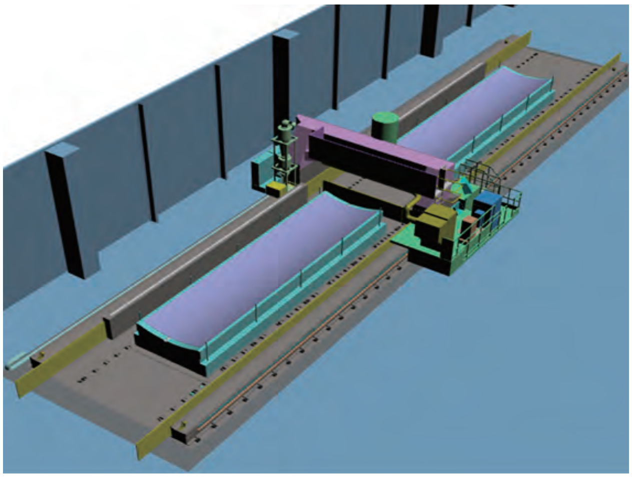


Fig. 6 Coordination hole drilling system with a high precision actuator

(a) Vertical installation

(b) Horizontal installation

Fig. 7 Final assembly jig

Fig. 8 Enhancement of automation using a riveting machine

(ii) Expansion of Automation

In the final assembly, we were able to automate the conventional work of manual installation. In addition to panel splice work, installation of machined integral frames and structures around doors were automated by the riveter shown in **Fig. 8**.

As part of the expansion of the scope of automation, we also introduced a new method that combines robots, equipment, jigs and tools. We reviewed the method that combined conventional drill templates and general-purpose power feed drills, and realized large-diameter drilling with high rigidity robots and the sub-assembly work that combined riveters and robots. Moreover, we also achieved multi-machine handling work by combining high rigidity robots and large jigs and tools.

Conclusion

We completed the delivery of the first 777-9 jet from Nagoya Plant 1 in February 2018. Next, The Boeing Company plans to acquire a type certificate after the first flight in 2019, and to start delivery to airline companies in 2020. Boeing has received orders for more than 300 aircraft as of the end of April 2018.

At present, we are proceeding with the development of the 777-8 as a derivative airplane, and we will progress with the development in cooperation with the Boeing Company to further increase efficiency and make improvements based on the experience we gained from working on the 777-9. Lastly, we would like to express our thanks to the International Aircraft Development Fund and Japan Aircraft Development Corporation for their guidance and support.

Reference

1) Japan Aircraft Development Corporation, Market Forecast for Commercial Aircraft, 2017-2036, pp. 26 (2017)
2) FAR Part 121 Sec. 121.291: Demonstration of emergency evacuation procedures

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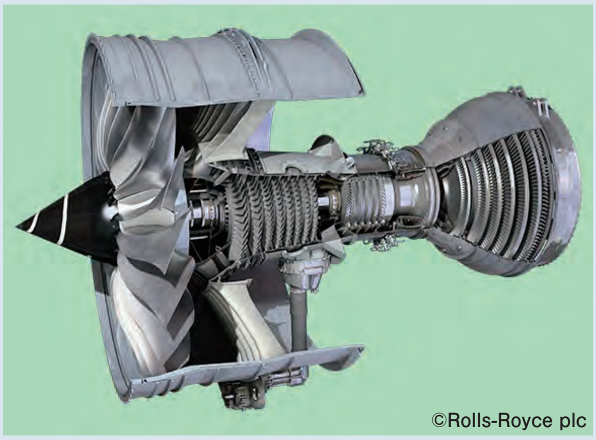
Development of Trent Series Large Turbo Fan Engines



As the demand for aircraft has been increasing, fuel efficiency needs to be improved. Therefore, the performance of the engine as well as the fuselage must be enhanced.

We are in charge of design, part manufacturing and module assembly of the intermediate pressure compressor (IPC) at development of all the Trent Series large turbo fan engines from Rolls-Royce after the Trent 1000, the first model of which helped develop in 2004, as their strategic partner. Going forward, we will promote activities to take charge of the overall IPC module as an IPC module integrator by developing proprietary design and manufacturing technologies.

Introduction

Aircraft are an essential means of transportation in global society, and aircraft manufacturers are competing to develop new types of aircraft. Engines equipping such aircraft must be highly reliable, lightweight and fuel efficient, as well as environmentally friendly (low NOx, low noise).

1 Background

The demand for aircraft is expected to grow by about 5% annually even in the long term, pushed by factors such as the rapid expansion of Low-Cost Carriers (LCCs). To meet such market needs, The Boeing Company in the US and Airbus in Europe are developing new types of aircraft. Rolls-Royce plc (Rolls-Royce) in the UK, one of the world's major aircraft engine manufacturers, has been developing and supplying its Trent series for such aircraft, and we are participating in programs to manufacture the series as a Risk- and Revenue-Sharing Partner (RRSP).

2 Development overview

The Trent series is a generic name given to engines made by Rolls-Royce for civil aircraft (wide-body), and all Rolls-Royce engines from Trent 700 on are in the Trent series, as shown in **Fig. 1**.

We have been manufacturing parts for all Trent series engines. Particularly for the Boeing 787's Trent 1000 program, we have participated in the program from the development phase including design, parts manufacturing

Fig. 1 Trent Series

and assembling the various parts of the intermediate pressure compressor (IPC) modules as well as supplying Rolls-Royce with the IPC modules[1) 2)]. Furthermore, in the Trent XWB for the Airbus A350 and the Trent 7000 for the Airbus A330neo programs, we have been handling the IPC modules as a strategic partner of Rolls-Royce. To survive as an IPC module integrator going forward, we need to continue to develop our proprietary technologies described later in this article to keep strengthening our capability to propose competitive products and modules to customers.

In addition, we will continue to contribute to the overall development engines by conducting endurance and other tests for many Trent series engines in our large engine testing facilities.

3 Characteristics of the Trent engines and modules, and our development subjects

The Trent series engines are characterized by their unique triple-spool structure having an intermediate pressure system in addition to the two conventional high- and low-pressure spools, as shown in **Fig. 2**. This intermediate pressure system turns the low pressure compressor (LPC), which would normally run only at low rotation speeds into an IPC that can run at optimal rotation speeds independently from fans that restrict the speed of rotation, increasing the system's efficiency.

Figure 3 shows an image of the IPC module specific to the Trent series, and **Fig. 4** presents a cross-section

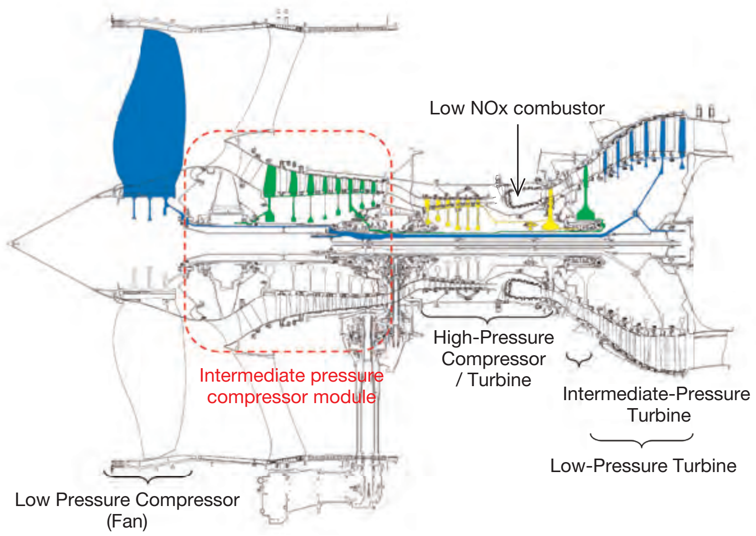


Fig. 2 Characteristics of the Trent Series (Trent 1000)

Fig. 3 Appearance of the IPC module

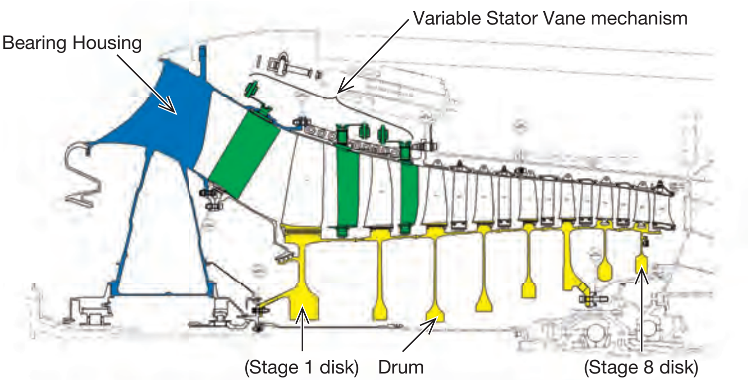


Fig. 4 Cross-section of the IPC module

drawing. The IPC module's unique features and our development subjects are described below.

① The Front Bearing Housing functions as a stator vane that rectifies the airflow from the fans to the engine core, as well as functioning as the main structure that holds the bearing. This requires a complicated design to accommodate oil and air passages while maintaining high strength.

② The IPC module has an eight-stage structure (the high pressure compressor (HPC) has six stages), making it the main part of the compressor. As it operates at higher rotation speeds than the LPC of a conventional twin-spool engine, high strength is crucial.

③ A Variable Stator Vane mechanism, which sits in the HPC in conventional twin-spool engines, is adopted in the IPC Module. The mechanism positions the Vanes with high accuracy corresponding to various flight conditions. The adoption of the mechanism made the IPC structure complex.

4 Design and development

(1) Our achievement

In the commercial aero large turbo fan engine market, the demand for safety, reliability, weight reduction, fuel efficiency, long life cycle and noise reduction continually increases year by year. Relentless efforts were made to keep meeting the demand. The significant performance improvements seen in recent years have been driven by a mixture of various technical studies and edge production technologies. Aerodynamic design has been studied, evaluated and demonstrated through rig testing and analysis, and the state-of-the-art production technology such as Linear Friction Welding (LFW) has been introduced. The Trent XWB series consumes 15% less fuel and is 15% lighter than conventional engines in the same class.

In the development of the IPC modules for Trent 1000, Trent 7000 and Trent XWB, we mainly took charge of structural and mechanical design and analysis, particularly contributing to increasing the accuracy of the Variable Stator Vane (VSV) mechanism, as well as reducing weight and extending the life cycle of the rotor disks.

(i) Highly accurate Variable Stator Vane mechanism

The IPC module's VSV mechanism shown in **Fig. 5** positions the angle of the stator vanes to rectify the main airflow streaming through the compressor. This enables compressors to work with high efficiency under a wide range of flight conditions. The higher compressor efficiency, the less fuel is consumed. Vane mechanism requires sufficient stiffness and being produced close to the nominal geometries to operate efficiently, stably and precisely as intended in the aerodynamic design. Aircraft engines, however, must be as light as possible. Parts of the Trent series large engines, whose diameters are large, are expected to be as thin as possible. Their large and thin walls make it difficult to reduce the mechanical tolerances or increase stiffness. Finite Element Method (FEM) analysis and a number of rig tests were conducted to optimize the layout and the thickness of the components comprising the VSV mechanism. The VSV mechanism is now not only designed as thin as possible but also as stiff as possible. It can manage massive airflow in highly efficient compressors.

(ii) Light and long life cycle rotor disks

The recent compressors run at higher speed, under higher temperatures, generating massive gas dynamic force as they become more efficient. As the operating conditions of the compressor rotors become more severe, it is necessary not only to prolong the life of the rotors for

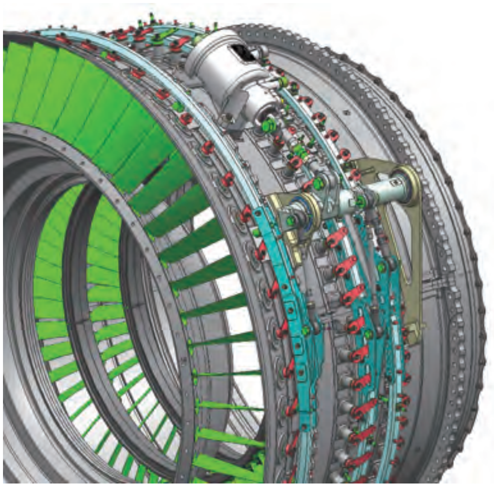


Fig. 5 Variable Stator Vane mechanism of the IPC module

cutting the life cycle cost but also to the further reduction of their weight. While the stress level has drastically increased compared to conventional aircraft engines, the disk stiffness has been reduced to its limit to minimize weight. Achieving minimal disk weight requires satisfying various conflicting conditions, such as optimizing rotor stiffness to maintain high compressor efficiency by an appropriate rotor-tip clearance. However, rotors need to have a long service life while enduring high stress. To alleviate this problem, we used design criteria that take into account every foreseeable risk, and optimized the design by incorporating various state-of-the-art analysis and production technologies, in addition to performing the conventional low cycle fatigue life evaluation and crack propagation life analysis.

(2) Our continuous journey

In the engine programs for civil aircraft we have joined, we have mainly taken charge of structural design and various analyses such as stress, thermal and vibration analyses. Going forward, we will expand our role to cover compressor design integration including aerodynamic design and compressor module system design (engine subsystem), and aim to be a so-called module integrator. To that end, we are conducting various research programs towards developing compressor modules for future large turbo fan engines.

(i) Compressor component technology development

To further improve the performance of compressors in large turbo fan engines, we are focusing on developing technology for designing blisks/blings, improving sealing performance, and improving the accuracy of VSV mechanisms.

Recently, the mainstream of compressor rotors design has been shifting from bladed disk to the blisk for further weight reduction and higher performance. As the compressor blisks with large outer diameter will rotate at high speeds under a massive dynamic force generated by airflow running through the compressor, technologies to suppress such phenomena as cascade flutter need to be developed. Consequently, conventional design methods and criteria are refined and analyses and rig tests are performed.

Compressor modules are furnished with numerous air sealings, and these are mainly labyrinth seals. Air leakage from seals causes the loss of compressor main and secondary air, decreasing compressor efficiency. And as the flight conditions influence sealing performance, it is challenging to maintain a high level of seal performance. Another challenge is to minimize the deterioration of seal performance in long-term use, contributing to cutting the life-cycle cost. One of the objectives in our research and development is new types of sealing for better performance and longer service life.

As the positioning accuracy of a VSV mechanism significantly influences compressor performance, we are analyzing the factors causing operational errors in order to develop and design parts for the mechanism based on a new concept. By reconsidering the layout of the mechanical system, we are aiming to achieve both lighter weight and higher accuracy positioning by integrating and/or increasing the stiffness of parts constituting the mechanism. Going forward, the objective is to achieve higher overall accuracy with a VSV system that includes actuators.

(ii) Compressor rig tests

We are redefining design criteria to design products that can meet stricter requirements and endure more severe conditions, assuming that they will be used in future compressors. We will employ rig tests to acquire data under stress, cycle and temperature conditions among others that cannot be obtained via conventional rig or material tests. Cyclic spin tests for compressor rotors, shown in **Fig. 6**, Fan Blade containment tests, and blade impact tests are planned.

(iii) Compressor module rig tests

We are conducting aerodynamic design and module system development of compressor modules, assuming they will be used for future large turbo fan engines. To demonstrate component technologies, including aerodynamics and system technologies, we plan to perform compressor rig tests at the company's facilities.

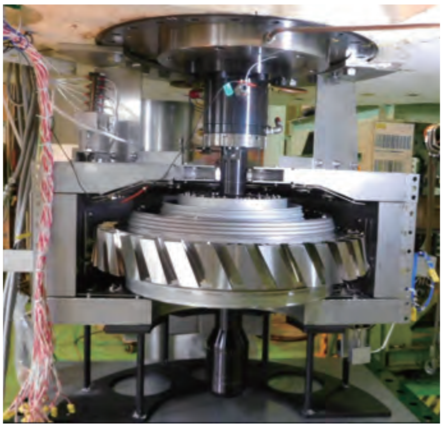


Fig. 6 Cyclic spin test rig and test unit

The plan involves designing compressor modules according to the above-mentioned criteria (redefined based on the component technology development and rig tests), and demonstrating them through compressor module rig tests to improve and mature our compressor technologies towards future engine programs.

5 Engine development tests

Our Akashi Works houses many gas turbine engine testing facilities (test cells), one of which is a large fan engine test cell for engine development tests for the Trent series. Since our cells passed both a commissioning and a cross calibration test using Trent 800 in 2000, we have performed many cyclic and endurance tests for Trent 500, Trent 1000, and Trent 7000.

Figure 7 shows an engine installed in the test cell. A cyclic test is a simulation test that repeats an operating pattern several thousand times to imitate real engine operating conditions. The purpose of this test is to assess how engine performance and its individual components deteriorate over time before fleet engines being mounted on the aircraft in service.

An endurance test is part of the testing regime required for the engine type certification; it is a critical test that engines must pass before airworthiness authorities such as European Aviation Safety Agency (EASA) and US Federal Aviation Administration (FAA) will certify them. It comprises a 150 hour-long test which includes particularly severe conditions, such as continuous operation at the maximum take-off power for 30 minutes, where it is allowed only for five minutes normally.

Fig. 7 Trent engine in test cell

In addition, cases sometimes arise when it is necessary to reproduce non-conformities observed during actual operation and perform improvement tests. In such situations, we conduct the tests together with Rolls-Royce, the test owner, as well as with aircraft manufacturers and engine component suppliers.

While engine design and development are conducted based on estimated operating conditions, engines must ultimately be verified through actual tests. Such engine tests, however, are those in a stationary state on the ground; the engine condition in flight won't be reproduced. Because of this, although feedback from actual operation is necessary, we are striving to contribute to the flight safety as much as possible by performing engine tests in Akashi.

Conclusion

The latest TEN configuration of the Trent 1000, whose IPC module we developed, has entered into service. Also, the -97 configuration of the Trent XWB, with higher thrust, has also started commercial operations. As the latest Trent 7000 is planned to enter into service, capability for mass-production is being built to consistently supply close to 600 units of the IPC modules per year. We will continue to develop our proprietary technologies in parallel with this, enabling us to supply competitive parts and modules for future aircraft engines.

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Reference

1) Kano: "Development of Trent 1000 Large Turbo Fan Engines," Kawasaki Technical Review No. 161, pp. 8-11 (2006)
2) Sera, Nagai: "Connecting Clean and Quiet Skies—Aircraft—," Kawasaki Technical Review No. 169, pp. 14-21 (2009)

Development of Small and Smart Target Drone: Cost Reduction Success with Proprietary Technologies

The aerial target drone systems are operated by the Japan Ministry of Defense for live fire training to protect our country from enemy threats. We developed the Small & Smart Target Drone Systems for simplifying and integrating its sub-system / structure / components due to the requirement of significant cost reduction.

Introduction

The Ministry of Defense is conducting firing training with autonomously flying aerial target drones as part of training to protect the country from aerial threats.

1 Background

The numerous aerial target drones developed inside and outside Japan so far are large and expensive. As it has not been possible to purchase a sufficient number of aerial target drones due to budget reductions for annual unit training, securing enough opportunities for firing training has been difficult.

2 Overview of small and smart target drones

(1) Operation overview

We have developed two types of small and smart target drones: the air-launched small aerial target for Japan Air Self-Defense Force (JASDF), and the ground-launched aerial target for the Japan Ground Self-Defense Force (JGSDF).

The air-launched small aerial target is used for air-to-air missile firing training by training aircraft. The drone is air-launched from F-15DJ mother ship in the JASDF training area, and it flies autonomously along the flight pattern set previously by the ground control equipment. The Operation is shown in **Fig. 1**.

In contrast, the ground-launched aerial target is used for firing training with ground-based antiaircraft weapons (such as missiles and automatic cannons), in which the target drone is launched from a launcher on the ground by a rocket motor.

(2) Drone overview

The air-launched small aerial target is one type a drone. As **Fig. 2** shows, the drone comprises a nose unit, a control and communication unit, a main wing unit, an engine unit, a steering unit and a tail unit. The nose and tail units are the same part.

(i) Aircraft structure

The fuselage is a monocoque structure comprising a metal tube, and the fins of the main wing unit and steering unit are solid structures.

(ii) Nose unit and tail unit

The nose unit and tail unit are equipped with Luneberg lenses to produce radar reflectivity close to that of a fighter, allowing the drone to be a target for a radar-guided missile. The lenses are covered by fairings to reduce aerodynamic drag.

(iii) Control and communication unit

The control and communication unit is a module functioning as the brain of the system. It consists of a GPS/INS navigation sensor that detects the drone's position, speed, attitude and so on, a computation circuit that performs flight-control and power-source management, an ATC transponder necessary for airspace safety, a signal transmitter and receiver to communicate

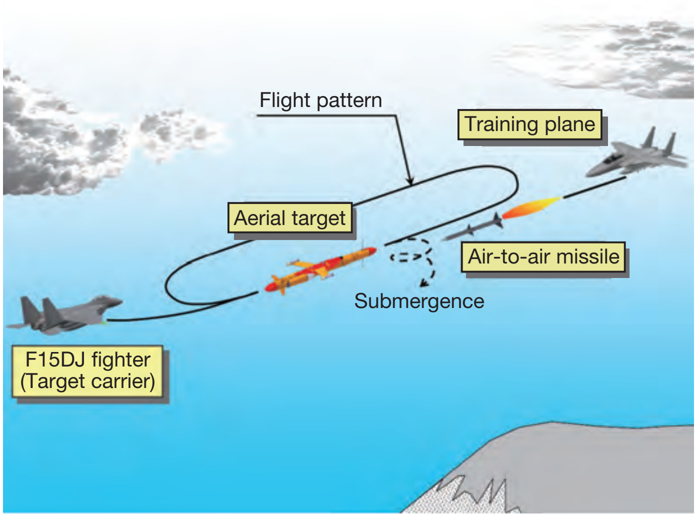

Fig. 1 Overview of operation air-launched small aerial target

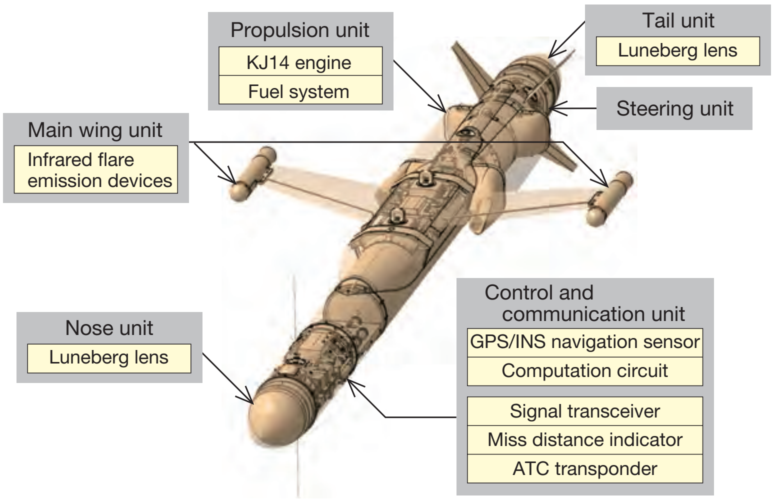

Fig. 2 Overview of drawing of air-launched small aerial target

with the F-15DJ mother ship or others, and a miss distance indicator that analyzes the distance to the passing missile.

(iv) Main wing unit

The main wing unit consists of the main wing structure and infrared flare emission devices attached to the main wing tips. The infrared flare emission devices ignite flares according to a command from the mother ship to allow firing training with infrared guided missiles.

(v) Propulsion unit

The propulsion unit comprises a fuel system and KJ14 engine. The propulsion unit uses the KJ14[1)] turbojet engine developed by us.

(vi) Steering unit

The steering unit consists of four all-flying fins. The drone is controlled by moving them in various combinations.

3 Policy of reducing cost

To develop small and smart target drones, the Ministry of Defense required us to drastically reduce cost compared with conventional target drones while maintaining the functionality and performance required for their firing training. To address this requirement, we decided to adopt the approaches of "simplification" and "integration," taking advantage of our proprietary technologies, considering that aerial target drones are unmanned aircraft and throwaways used only for a short time.

4 Cost reduction with our proprietary technologies

(1) Cost reduction by simplification

(i) Small engine

The KJ14 shown in **Fig. 3** is a single-spool turbojet engine designed for propelling a small unmanned aircraft.

Its compressor rotor and turbine rotor are integrated into a monorotor (an integrated structure made by precision casting) as shown in **Fig. 4**, and it uses a cantilever structure supporting only the low-temperature side at the front of the engine for simplification and lighter weight. This differs from support structures at both ends.

Furthermore, placing its bearings in the low-temperature part provides the additional advantage of allowing easier lubrication and cooling. To lubricate the bearings, considering that the engine is used only for a short time, a grease-filled bearing system is used to avoid the maintenance task of oil filling, which would be required for a separate lubrication system. Windmilling (rotation of a rotor by air flowing into the engine) starts the engine used together with a simple ignition cartridge. This design has not only reduced the cost, but has also made the engine smaller and lighter.

(ii) Fueling system

When starting the engine, fueling uses initial pressurization on the bladder tank, the shut-off valve and

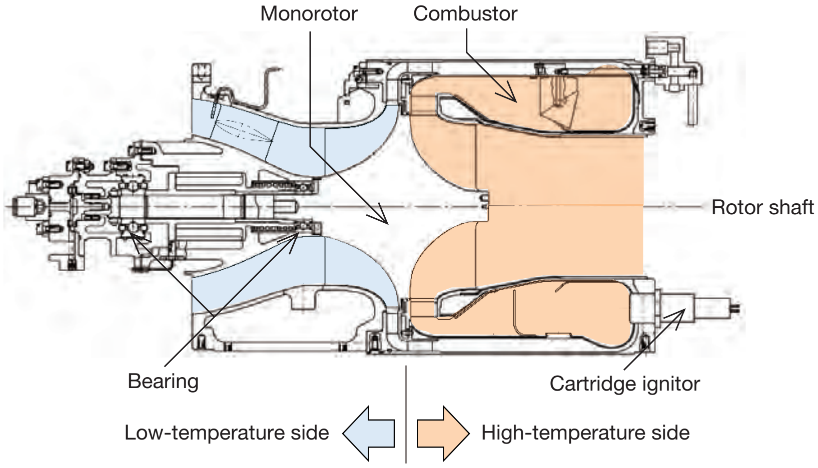

Fig. 3 Overview of drawing of KJ14 turbojet engine

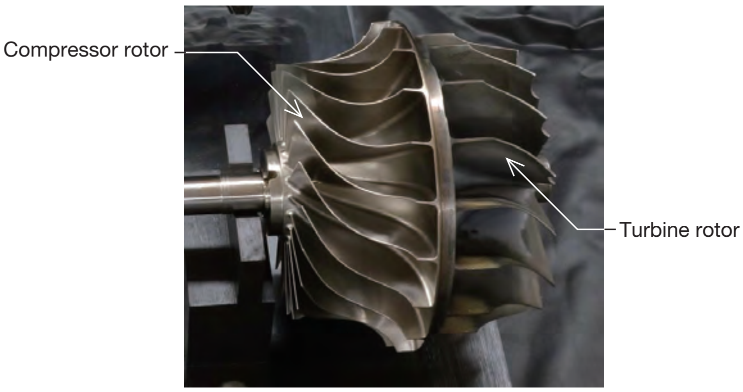

Fig. 4 External view of monorotor

the flow-control valve. Once the engine starts, it relies on the engine exhaust pressure, the fuel pump placed coaxially with the engine, and the flow-control valve for stable fueling. As **Fig. 5** shows, this design has produced a simple and highly reliable fueling system with a small number of parts without needing an expensive booster pump, fuel pump, and valves.

Although the bladder tank system used in this drone is inferior to an integral tank system in terms of space optimization, it is an outstanding system that eliminates two problems: that of irregular impact loads caused by fuel sloshing around; and a poor fuel supply due to air getting into the fuel piping.

(iii) Flight control system

Since there was no maneuverability requirement involving ascending and descending while flying, and to reduce cost, we decided not to use a pitot tube (which needs precision machining and precise instrument calibration) as shown in **Fig. 6**. Instead, this drone employs a GPS/INS navigation sensor alone for the flight control system and to estimate airspeed and altitude essential for flight control calculations.

The flight control system estimates airspeed based on the attitude measurements sent from the GPS/INS navigation sensor and a database of speed and attitude obtained from wind-tunnel tests. Altitude is estimated by

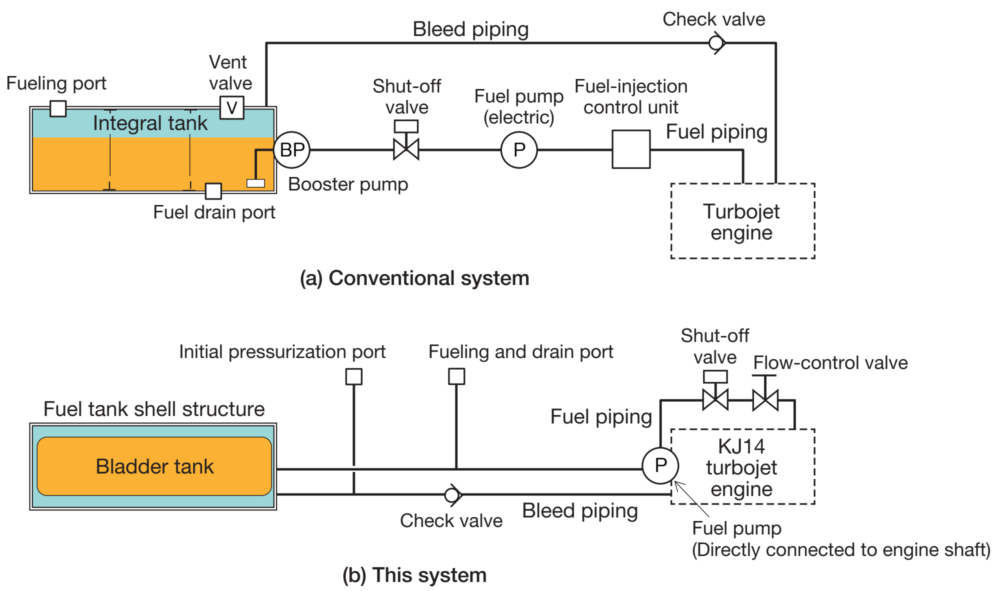

Fig. 5 Simplification of fuel supply system

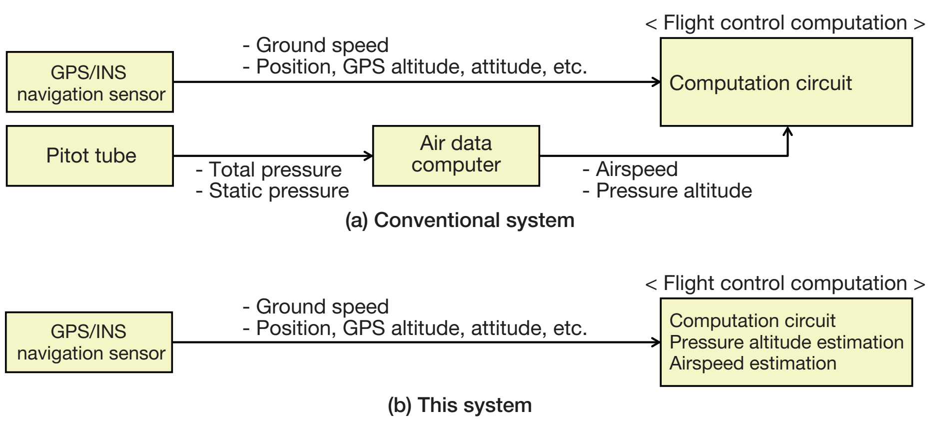

Fig. 6 Simplification of flight control system

comparing the drone's GPS altitude and the flying altitude of the carrier plane at the time the drone is launched. We have confirmed that this calculations works correctly comparing the estimated values with measured values obtained from calibrated instruments installed on manned aircraft.

(2) Cost reduction by integration

(i) Aircraft control — engine control

Since the aircraft body manufacturer has to date been different from the engine manufacturer in aircraft development, much effort goes toward interface adjustment. With this drone, however, as both the airframe and the engine were developed by us, it was relatively easy to integrate the aircraft control and engine control, and the size of the control circuit unit was reduced by half as shown in **Fig. 7**.

(ii) Engine mounting

To minimize the number of parts and reduce the assembly and machining workloads, the engine is mounted in a unique way whereby it is directly connected to the aircraft as a primary structure of the body as shown in **Fig. 8**, instead of being mounted as a pod in conventional drones.

(iii) System integration

Electromagnetic compatibility testing is a test to check whether the level of generated emissions does not exceed the specifications and the irradiated noise does not cause malfunctions. This is to prevent electromagnetic interference on the drone itself and the F-15DJ fighter by unnecessary electric noise emitted from the electric devices (emission).

We achieved cost reductions when developing this drone by fulfilling the requirement for an integrated aircraft system as shown in **Fig. 9**, instead of needing electromagnetic compatibility testing for individual devices. In addition, we applied ready-made products such as Commercial Off-The-Shelf (COTS) products, mainly for electronic components such as the computation circuit, communication equipment, and GPS/INS navigation

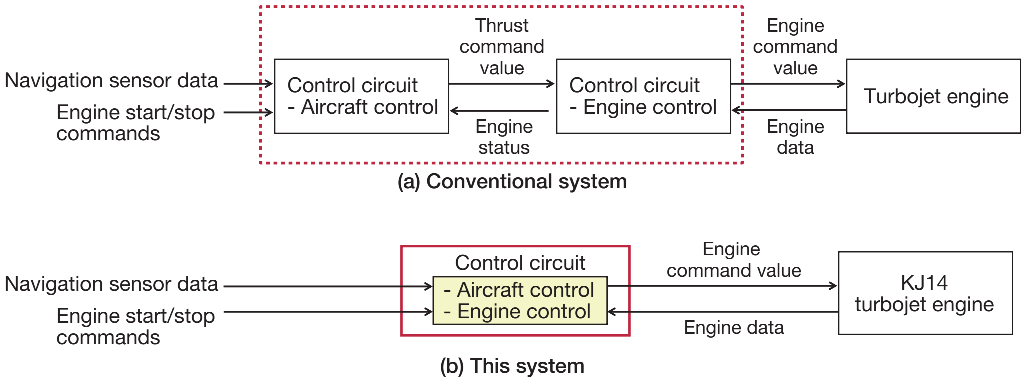

Fig. 7 Flight Control system incorporated with engine control system

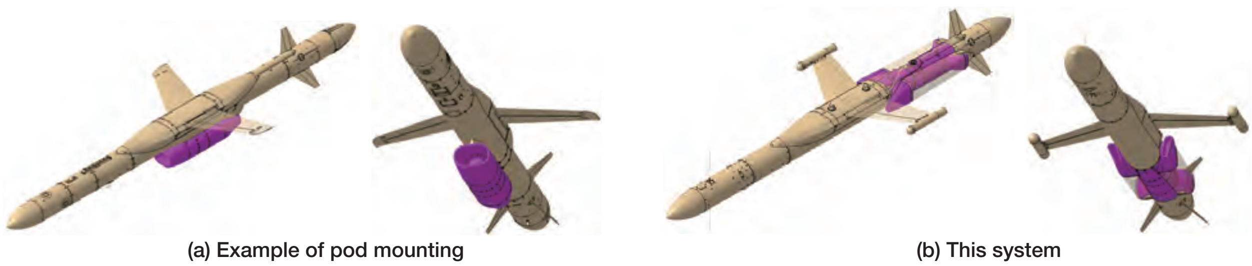

Fig. 8 Overview of engine installation

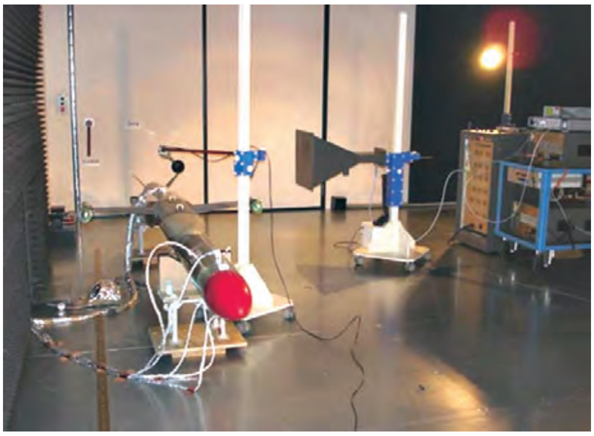

Fig. 9 Electromagnetic compatibility testing of whole aircraft

sensor. However, we have been able to keep costs low by modularizing the components and guaranteeing environmental durability for factors such as temperature, humidity and vibration required for military products instead of dealing with each part individually.

Conclusion

In developing this air-launched small aerial target, we have significantly reduced costs compared with conventional aerial targets. The small and smart target drones, including the ground-launched aerial targets for the JGSDF, are rated highly in terms of price and performance by the customer, the Ministry of Defense. This is due to the synergy effect in our company, which develops both the aircraft body and engine.

Pursuing further synergy, we will continue to provide defense-related instruments and equipment that has outstanding cost performance.

Reference

1) Nagata, Satake, Maeda, Kaneda, Ichimura: "Development of KJ14 Small Jet Engine," Kawasaki Technical Review No. 161 pp. 12-15 (2006)

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Development of Payload Fairings for Launch Vehicle

It is expected that launches of satellites will continue to increase in the future across the world including emerging and developing countries due to the benefits of images and positional information acquired by satellites. The fairing is a component that protects satellites on the top of the launch vehicle. This component plays an important role in the satellite launch business because the temperature and acoustic vibration environment around the satellite is critical along with the launch cost and the orbit injection accuracy.

Kawasaki has successfully produced a large fairing for the H-II Launch Vehicle for the first time in Japan. Since then, we have made technical improvements on an ongoing basis to continue supplying high-performance fairings at a low cost.

Introduction

National security, disaster prevention and private services that use images and positional information acquired by satellites have become common, and the space industry market is expanding. On the other hand, the entry of American entrepreneurs into the satellite launch business is exerting downward pressure on prices. This is leading to the need to supply high-performance launch vehicles at lower prices.

1 Background

There are two types of satellites. One is government satellites as represented by reconnaissance and weather satellites; the other is commercial satellites as represented by communications and broadcasting satellites. In the satellite launch business, aerospace companies from Japan, the US, Europe and Russia have continued to compete against one other for 20 to 30 commercial satellites a year. In 2010, however, as Space Exploration Technologies Corp. (SpaceX) made inroads into this business with its low-priced Falcon 9 launch vehicle, prices plunged. Moreover, the progress of launch vehicle technology from emerging countries such as China and India is remarkable, and competition is expected to further intensify in the future. Consequently, Japan, the US and Europe are now promoting development of next-generation, cost-competitive large launch vehicles, and plan to put them on the market in about 2020.

Since developing the payload fairing for the H-II Launch Vehicle in 1984, Kawasaki has continued to improve its technology through the H-IIA/H-IIB Launch Vehicles and the Epsilon Launch Vehicle[1)], and now supplies payload fairings for all of Japan's major launch vehicles. At present, Kawasaki is in charge of developing the payload fairing for the H3 Launch Vehicle, and is engaged in developing of high-performance payload fairings at low cost with the aim of launching the first vehicle in fiscal 2020.

2 Payload fairing

As **Fig. 1** shows, a payload fairing keeps the internal temperature/humidity and cleanliness (in the space where a satellite is mounted) constant until the launch vehicle lifts off, and reduces aerodynamic drag during the flight. At the same time it helps to protect the satellite from aerodynamic heating and acoustic vibration. Once the launch vehicle reaches an altitude of about 100 km, where the atmosphere is sufficiently rarefied, the payload fairing splits into two pieces by actuating its separation system, rotates on a hinge and separates from the launch vehicle.

Figure 2 shows the structure of payload fairing. It has two half-shell bodies that are joined together by the separation system (vertical separation system) in the axial direction, and they are joined to the body of the launch vehicle by the separation system (horizontal separation system) in the circumference direction. The payload fairing

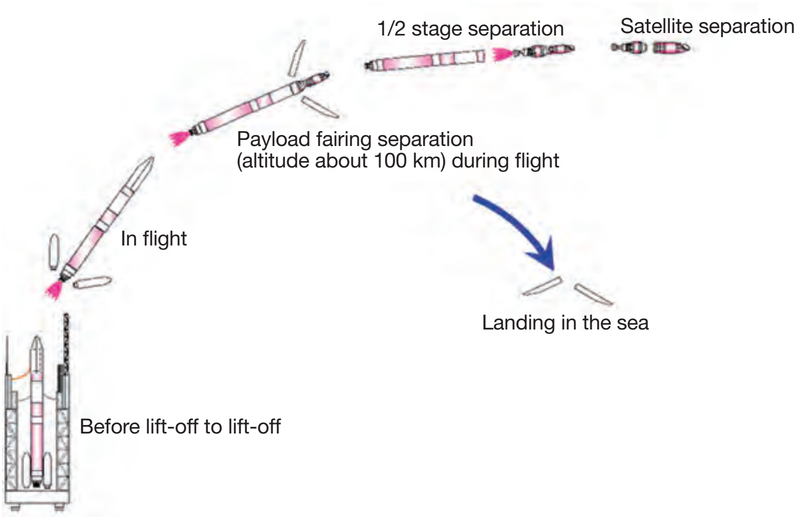


Fig. 1 Launch sequence

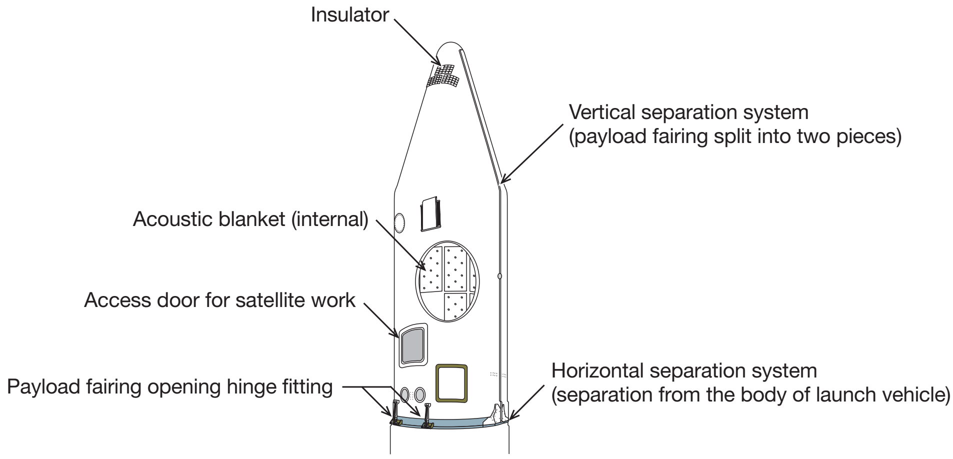


Fig. 2 Configuration of payload fairing

has an access door used by satellite crew for maintenance and a radio transparent window for communication between satellites and their launch facilities. Moreover, the payload fairing has an air-conditioning door draw in clean air into the inside at the launch facility, insulators to prevent the body structure and interior from heating up due to aerodynamic heating, and an acoustic blanket as sound-absorbing material to reduce acoustic vibration caused by engines and the atmosphere.

To minimize the weight of the satellite, which has many delicate electronic components aboard, it is important to ease the environmental conditions around the satellite such as heat, acoustic vibration and shock. This is the role payload fairings play.

3 Technology to support payload fairings

(1) Separation systems

Separation systems are the most technically difficult components of payload fairings to design and make. As separation systems are strength members that connect structures, they must be strong enough to endure the aerodynamic loads generated at supersonic speeds. Yet the strength needs to be low enough to separate payload fairings with minimal energy to reduce the shock to satellites during separation. This means payload fairings must be designed to bring such mutually contradictory requirements into balance. As faulty payload fairing separation directly leads to mission failure, high reliability is critical.

Kawasaki has decided to develop Japan's unique separation system based on the frangible bolt (notched bolt) method. This method was used in a canopy emergency separation system for fighter aircraft at the time when development of the payload fairing for the H-II Launch Vehicle was underway. Priority was given to higher reliability and lower cost. This method employs explosive force to cut a bolt that features a V-shaped groove (notch) for easier cutting. Although development took a long time, as even slight changes in parameters of materials, notch shapes and plate thickness of stainless steel oval tube cause bolt uncut or oval tube ruptures that lead to faulty separation and satellite contamination, the great number of tests have resulted in highly reliable separation systems that are can be applied new types of fairings even today (**Fig. 3**).

(2) Environmental mitigation

(i) Insulators

To prevent rises in temperature of body structures due to the heat caused by the friction against the atmosphere, and maintain appropriate temperatures around satellites, insulators are applied to the outer surfaces of payload fairings. Kawasaki developed a light-weight insulator for the payload fairing of the H-II Launch Vehicle by mixing glass microballoons into silicone resin, and achieved both weight reduction and heat insulation improvement at the same time.

(ii) Acoustic blanket

To reduce acoustic vibration caused by engines and friction against the atmosphere, acoustic blankets are applied to the inner surfaces of payload fairings. Glass wool and resin foam are used for this insulator, and the insulating material is packed in filter-equipped covers to

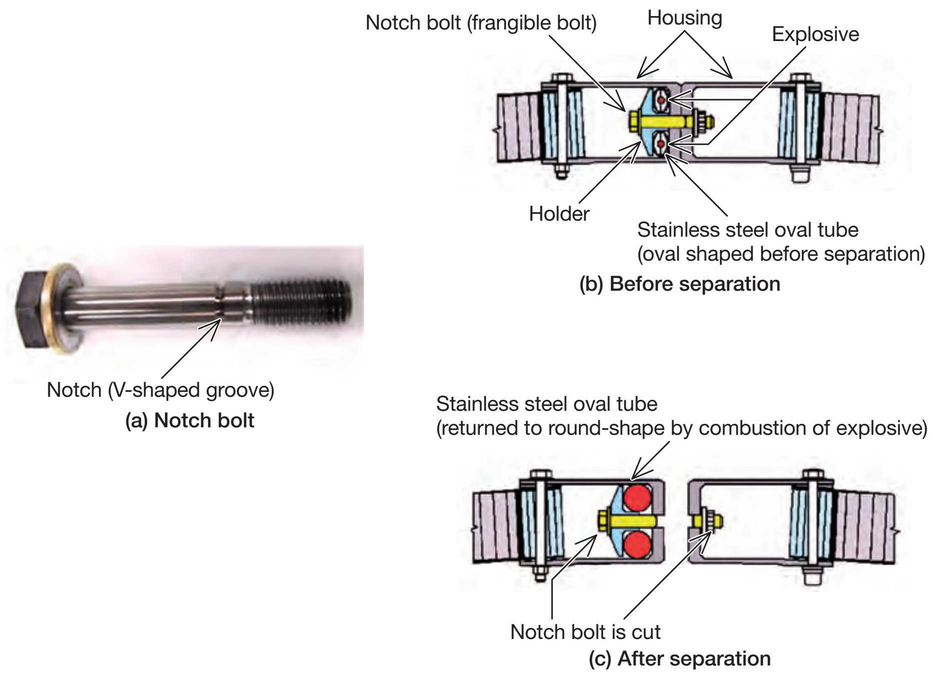


Fig. 3 Separation mechanism of payload fairing from Kawasaki

prevent dust from escaping into the satellite compartment. The aim is to prevent the covers from rupturing in decompressed environment as the launch vehicle climbs. This means decompression, in addition to weight minimization, is also an important factor in designing launch-vehicle equipment.

(3) Structure and shape

(i) Structure

Conventional payload fairings have a lightweight and highly bending stiffness honeycomb sandwich structure that can reduce deformation at the time of opening as much as possible and reduce aerodynamic drag, ensuring more space to carry satellites within a smaller diameter.

The sandwich structure joins thin plates to both sides of a lightweight core material. The advantage of this structure is that increasing the core thickness makes it very difficult for the sandwich structure to deform while minimizing any weight increase. A structure that uses a honeycomb core for its core material is called a honeycomb sandwich structure. Honeycomb core materials include aluminum alloys and meta-aramid fibers. And as for skin materials, aluminum alloys and carbon fiber reinforced plastics (CFRP) are often used.

Kawasaki's payload fairings usually use aluminum alloy-honeycomb/aluminum-alloy skin structures, but CFRP skins are also used for lower payload fairings that require weight reduction in some cases.

(ii) Shape

The H-II is a four-meter-diameter launch vehicle capable of launching a four-ton satellite into geostationary transfer orbit (GTO). The masses and shapes of satellites vary from mission to mission, and these include payloads such as four-meter or larger diameter mega-satellites and two-ton or less small satellites. As **Fig. 4** shows, therefore, to increase the usefulness of launch vehicles, a five-meter-diameter payload fairing (5S) for mega-satellites and payload fairings (4/4D-LS, 5/4D) capable of carrying two satellites at the same time were developed.

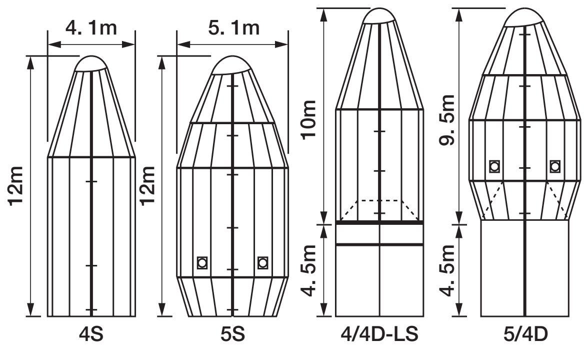


Fig. 4 Forms of payload fairings

To cope with the increased variations of fairings, many different molds are needed to shape the payload fairings, and many assembly jigs and tools are required. However, to reduce non-recurring costs as much as possible, we have achieved commonality of panels among respective types of payload fairings, and jigs and tools include length-adjusting functions and other ideas.

4 Approaches to new technology

(1) Approaches to the Epsilon Launch Vehicle

The development of payload fairings for the Epsilon Launch Vehicle started in 2010. For this project, Kawasaki addressed new technology development by following the designs of the H-II series such as H-IIA/H-IIB with the aim of reducing costs and improving convenience.

(i) Half-shell integrally submerging body structure

Payload fairings that separate from launch vehicles and land in the sea do not submerge but float because of the hollows in their honeycomb structure. In Japan, to avoid floating payload fairings from hindering the navigation of ships, they are recovered by ships after lift-off. However, as the cost of recovery is high and recovery depends on the weathers, payload fairings are now required to submerge.

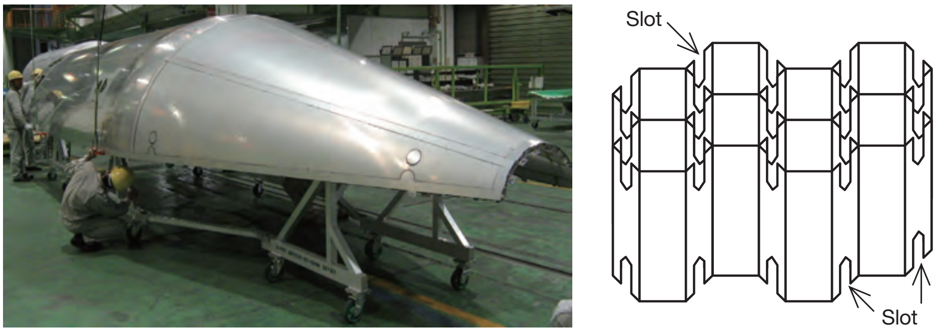
Therefore, the sound-absorbing honeycomb cores of aircraft engine nacelles are now applied. These honeycomb cores are added with slots on cell walls as shown in **Fig. 5** to drain rainfall water and cleaning water. When applied to the payload fairings, this structure allows sea water to enter the panels and sink them.

In the H-II series, two or more panels are joined together by bolts to make a half-shell body structure. In the case of the payload fairing for the Epsilon Launch Vehicle, the assembly cost was reduced as the half-shell integral molding was made possible by the slightly curved surface shape of the joint between the top cone and cylinder body.

As for the half-shell integral molding, these was a manufacturing problem where it was difficult to access the top of the half-shell panel when laminating the components such as skins, cores and adhesives. We solved the problem by creating appropriate shaping dies and scaffolding after repeated simulations that used three-dimensional CAD at the time of designing the jigs and tools.

(ii) Sheet-pasting type insulator

In the case of payload fairings for the H-II series, the aforementioned silicone insulator containing glass microballoons was spray-coated in the dedicated coating booth. However, as it took a long time to dry the insulator,



(a) Half-shell integrally molded panel (b) Core with slot

Fig. 5 Structure of the Epsilon's payload fairing

the coating step constrained production in some cases in proportion to the increase in the number of payload fairings to be produced. We developed a new method to paste sheet-shaped silicone foams with adhesives. This method made it possible to insulate payload fairings in the assembly area, removing that constraint.

(iii) Quick-access door

As the Epsilon Launch Vehicle uses solid propellants, it is unnecessary to take much time to fuel it immediately before lift-off, unlike liquid-propellant rockets. To capitalize on this lift-off readiness to the greatest extent, an invention was required to shorten the maintenance time of launch vehicles and satellites by shortening the time to close access doors of payload fairings.

(2) Approaches for the H3 Launch Vehicle

As mentioned at the beginning, future launch vehicles will need to be cost competitive. The H3 Launch Vehicle is aimed at providing high reliability and flexible services appropriate to satellite missions at low cost. We are taking the following approaches when it comes to payload fairing development:

(i) Introduction of Automated Fiber Placement (AFP)

To simultaneously cope with the reduction in production cost of body structure panels and increase in the number of payload fairings to be produced, Automated Fiber Placement (AFP) will be introduced, and CFRP will be installed at low cost.

AFP is applied to the production of Boeing 787 fuselages and is also being widely introduced in the US and Europe. However, new technology will be required for placing it on honeycombs. For example, it will be necessary to fix honeycomb cores in dies and apply appropriate tension to prevent CFRP to hanging over between cell walls.

(ii) Using Out of Autoclave adhesive technology

In the case of payload fairings for the H-IIA/H-IIB Launch Vehicles, body structure panels are joined together by nuts and bolts. The H3 Launch Vehicle, however, uses Out of Autocrave adhesive technology to simultaneously reduce the mass and cost by employing adhesive technology to the greatest extent possible.

Compared with autoclave molding that is performed at five to six times atmospheric pressure, as components are pressed and bonded at vacuum pressure, if degassing before heating is not sufficient, voids are formed in adhesives, reducing their strength. Therefore, we needed to modify the jigs and tools after repeated coupon tests to create production conditions that sufficiently reduce voids. Preparations are underway toward producing actual payload fairings by bonding curved panels that simulate the top of the payload fairing, as **Fig. 6** shows.

(iii) Demonstration of synergetic effects between different types

In addition to the technologies outlines above, we plan to improve those technologies acquired through the Epsilon Launch Vehicle project, such as the submerging structure, the quick-access door and sheet-type insulator, and apply them to our payload fairings. There are also plans to develop a new version of the Epsilon Launch Vehicle. In the future, we see opportunities for efficiently evolving our payload fairing technology by applying the synergy existing between different types of launch vehicles such as the H3 and the Epsilon.

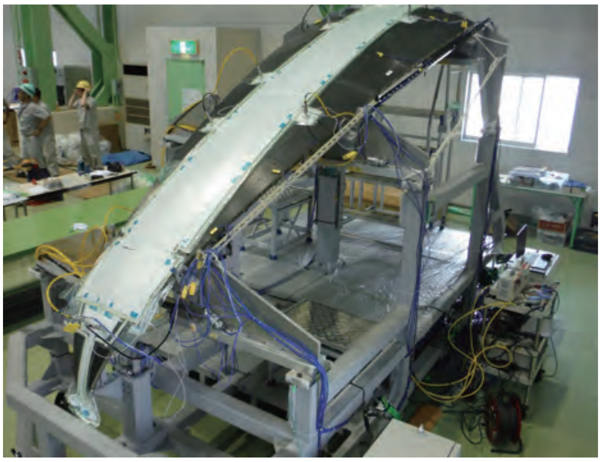


Fig. 6 Out of Autoclave joining of curved panels

Conclusion

In the future, emerging countries are expected to make inroads into the satellite launch business, and cost competitiveness will be more important than ever before. We aim to maintain our international competitiveness by bringing together our in-house technologies and continuing to develop and expand our payload fairing business into the future.

Reference

1) Komada, Horie, Tsutsui, Sekine, Kobayashi, Hirano, Koda, Sato, Onikura, Fukuno, Tagawa, Toyoda: "H-IIB launch vehicle fairing for space station transfer vehicles (HTV)," Kawasaki Technical Review No. 171, pp. 20-23 (2011)

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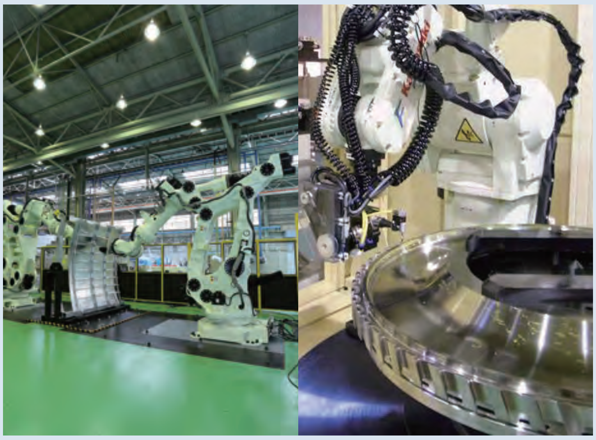
Development of New Joining and Finishing Technologies for Aircraft Fuselages and Engines Using Robots



More jetliners are expected to be manufactured in the future in line with an increase in the demand of plane passengers.

Automation using robots is garnering attention in the field of aircraft manufacturing since it is required to further reduce production costs and accelerate the production rate while satisfying stringent quality requirements. In this context, we are developing robots, systems and production processes suitable for automation and are moving ahead to apply them to actual parts of aircraft fuselages and engines.

Introduction

Over the next two decades, air traveler numbers are expected to increase by 4.6% a year on average, and it is anticipated that 33,000 new passenger jets will take to the air in the same time. On the other hand, price competition is becoming increasingly intense, and customers are demanding lower manufacturing costs.

1 Background

Recent years have seen not only the development of fuselages for the Boeing 777X and Airbus A350, but also engines for them, and even more new passenger plane models are also expected to enter development. As a partner in the joint development and joint production of aircraft fuselages and engines, it is critical for Kawasaki to focus on sophisticated quality control, cost reduction, higher production rates and weight reduction. To address to meet these requirements, we are promoting the development of both automation technology and new production technology. In particular, we are concentrating on automation by robots, which are less expensive and more flexible than dedicated equipment.

2 Policy to Apply Robots to New Joining and Finishing Technologies

(1) Fuselage Production

As for aircraft fuselages, we are considering applying the Refill FSJ (Friction Spot Joining), which was developed by our company. To date, we have evaluated prototype components and joint coupons produced by robot equipped with the standard C-type FSJ gun[1]. However, because the shapes of some components makes it difficult to use a standard FSJ gun, it became necessary to develop robot and control technologies that enable joining of components of various shapes, including large primary structures.

To solve this problem, we are developing methods and systems for joining by placing robots that independently hold FSJ guns and backing guns opposite each other, as shown in **Fig. 1**[2]. In this way, for example, it becomes possible to join parts that are mounted on the fuselage skins, such as the large components in the section we are responsible for producing for the 777X. This robot is a high-rigid robot named the MG10HL, newly developed to retard distortion caused by the reaction force at the time of joining. It has a function to correct slips caused by the pressure that is applied at the time of coordinated action and joining by two robots.

In this way, while developing robots and their control technologies for applying the Refill FSJ, we are also considering robot systems, including their layouts and how they hold joined parts.

(2) Engine Production

Aircraft engines can be classified into static components as represented by cases and stator vanes, and rotor components as represented by disks and rotor

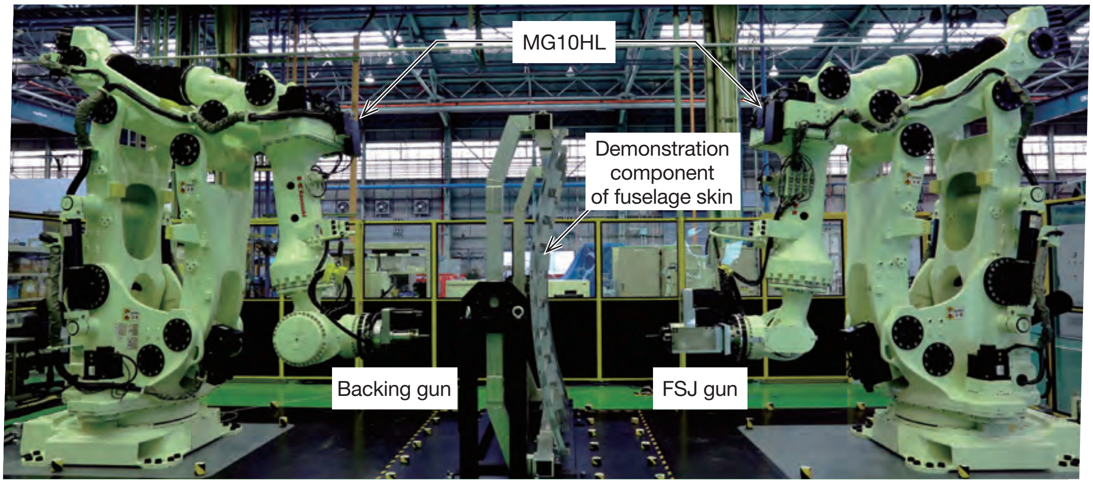


Fig. 1 Coordinated refill FSJ robot system

blades. Particularly as rotor components turn at very high speed, if they have a slight flaw or a dent, a crack can suddenly propagate from such a point, leading to the engine exploding in the worst case. As even a slight flaw could lead to a serious accident like this, stringent requirements and standards are applied also to hand finishing. To satisfy these requirements, we need advanced quality control, highly precise processing technologies and stable production quality.

To date, the edge finishing of such important rotor components has depended on the skill of experts. To realize the automation that meets customer requirements, we have independently developed technologies that make full use of robots, and have eventually become able to satisfy the requirements and standards. At present, we operate more than 20 pieces of robot finishing equipment. They are also applied not only to disk components, but also to gear parts and static components such as cases, realizing automated manufacture for multiple customers.

We have a policy to expand the scope of applying robots in the future, not only to finishing processes but also to other fields such as assembly work, parts distribution and loading/unloading of works to and from processors.

3 Considering Applications for Robots

(1) Aircraft Fuselage Production

(i) Development of Refill FSJ Process by Coordinated Robots

Figure 2 shows the Refill FSJ's joining process. Friction heat is generated by rotating the probe and shoulder

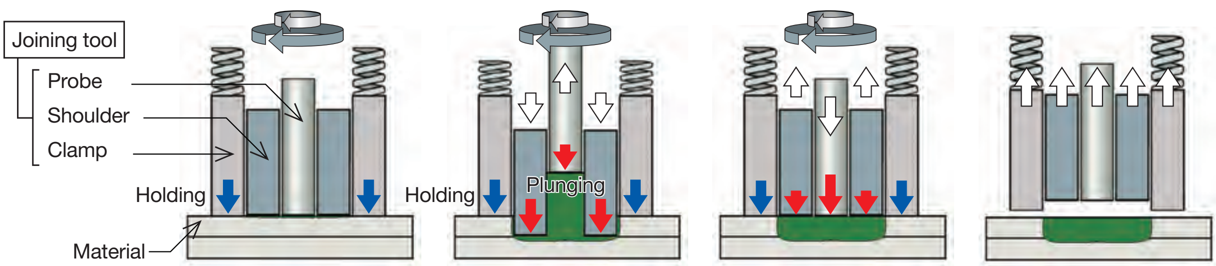


Fig. 2 Joining process of refill FSJ

together and pressing them to the material for softening, and while raising the probe and releasing the softened material, the top of the shoulder is pressed into the material. The upper and lower materials are integrated by causing plastic flow around them. Then, while pressing down the probe and backfilling the released material, the shoulder is raised.

To achieve good joining quality, we control parameters in respective processes such as probe position, tool load, rotation speed of the shoulder and probe, and plunge depth of the shoulder. To realize joining by coordinated robots, we need to synchronize the timings to start and finish respective processes and those of press-fitting and backfilling for the two robots.

(ii) Development of Joining Processes of Corrosion-Protected Materials

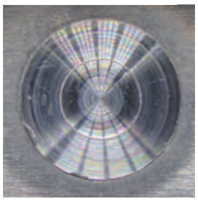
Many aircraft parts are coated with sealants to protect against corrosion at fay surface and for waterproofing. In principle, aircraft parts joined by Refill FSJ should be coated with sealant. However, if Refill FSJ is done by the joining processes described above, sealants would be caught in the joint, causing internal defects and loss of strength.

To prevent this problem, we developed a joining process for sealant-coated materials[3]. The process involves squeezing out the sealant that is coated on faying surfaces by applying pressure to the material with the joining tool before the Refill FSJ joining process begins. **Figure 3** shows a cross-section of a joint joined by this process. This is a good joint cross-section that has almost no sealant caught in the joint. The strength of the joint is significantly greater than those joints with no squeeze-out, and tests confirmed that the strength is nearly equal to that of joints not coated with sealants.

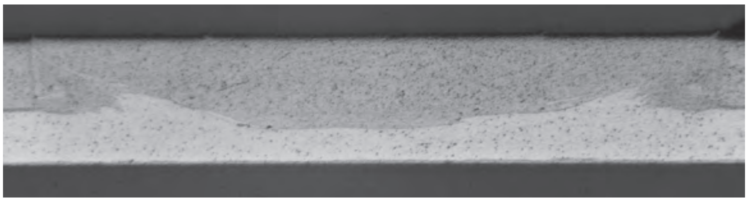
(iii) Automation of Component Layout

To automate the entire process of component production, we considered methods for having robots automatically lay out components, position them and hold them, and have prototyped systems to do so.

To avoid interference between the FSJ guns and parts, as shown in **Fig. 4**, we employ a small 10-kilogram portable robot called the RS10N is equipped with a light-weight



(a) Appearance of joint



(b) Cross-section of joint

Fig. 3 Joint appearance and cross-section in the joining process with the sealant squeeze-out

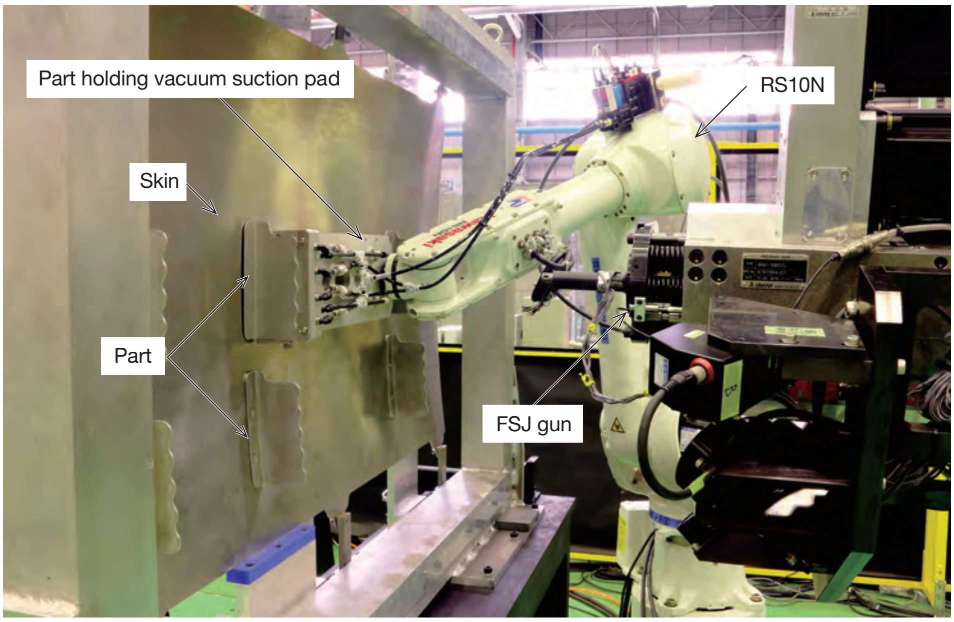


Fig. 4 Parts layout robot

vacuum handling tool to hold parts. We prototyped a system to control a total of three robots in a coordinated manner, i.e., two robots that have FSJ guns and backing guns and this part-layout robot. In doing so, we considered ensuring space to allow the FSJ guns to access joints, holding positions against reactions during joining and preventing flaws in parts. The vacuum suction made it possible to grasp parts steadily and provides clear access for FSJ guns by ensuring space around joints. Vacuum suction also made it possible to hold parts, including skins, in position and counter reactions during joining. **Figure 5** illustrates how resin blocks are laid out on contact surfaces between skins and vacuum pads to prevent flaws.

In future research, we will consider sensing and correction technologies to realize highly precise part layouts required for aircraft.

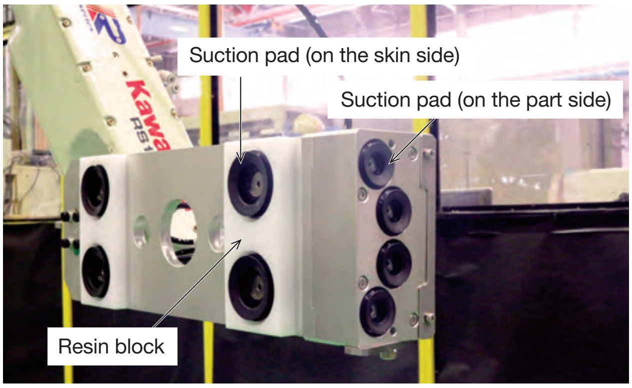


Fig. 5 End effector for holding the part

(2) Engine Production

(i) Off-line Teaching System KCONG

Usually, when motions are taught to robots on-line, robots are actually operated by people using teaching pendants. However, it is difficult to realize those motions that require precision to tenths of millimeters. To solve this problem, Kawasaki Robot has a unique off-line teaching system called KCONG (Kawasaki Common Offline NC data Generator) that makes it possible to teach complicated motions in a highly precise manner.

For example, in the case where works are machined by cutting tools mounted on robots, KCONG captures 3D models of applicable works first. Then, it creates teaching points on a personal computer as shown in **Fig. 6**, and produces machining paths for the cutting tools, making it possible to teach precise machining positions and achieve ideal motions for cutting tools.

(ii) Touch-Sensing System

With KCONG, while ideal teaching points can be found for robots, there are various problems with operating actual ones. Deviation from ideal motions is caused by absolute precision errors held by robots themselves and deflections of arms due to processing attitudes. Furthermore, works themselves do not necessarily have shapes exactly the same as those of 3D models and have individual differences within tolerances. Deviation can also result from errors that caused at the time of setting works to jigs and tools.

To compensate for the problems discussed above, we developed a touch-sensing system. This makes a three-point measurement of a part of a work in a state of being

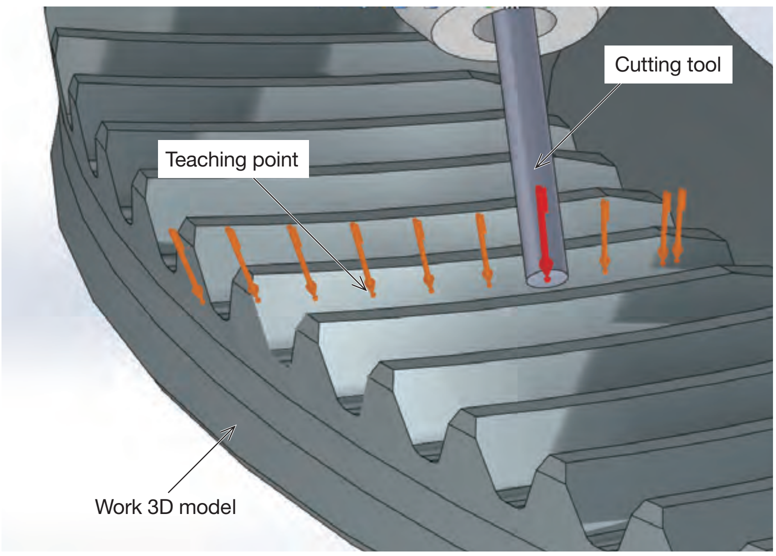


Fig. 6 Example of offline teaching with KCONG

set, derives the difference between the configured intersection point and the theoretical value, and then makes corrections.

(iii) Constant-pressure device

Even though ideal machining paths are obtained and moreover the positional deviation from the reality is corrected, uniform chamfering shapes are not necessarily obtained in all machine paths. This is because motions of robots themselves are not smooth, leaving problems in uniformity depending in some cases on the worn condition of cutting tools. In the case of processing by humans, uniformity is maintained by the skills of experts; for robots, however, other solutions are needed.

A device developed for this purpose is the constant-pressure device shown in **Fig. 7**. This device keeps the pressing force of cutting tools constant by controlling the torques of servomotors. It eliminates nonuniformity of chamfering shapes in machining paths and can achieve further quality improvements.

In realizing finishing by robots like this, it now possible to consistently achieve quality that is not inferior to experts through the development of various technologies and applying ideas to applications. As a result, we could satisfy customer requirements with regard to important rotors that require very strict quality standards. At present, robots also contribute to reducing work man-hours through application to those components that produced in volume.

In the field of aircraft engines, the application of compressors to rotor components is increasing, and robot-finishing is already applied to many types and volume-produced types of engines. Also, edge finishing of cases

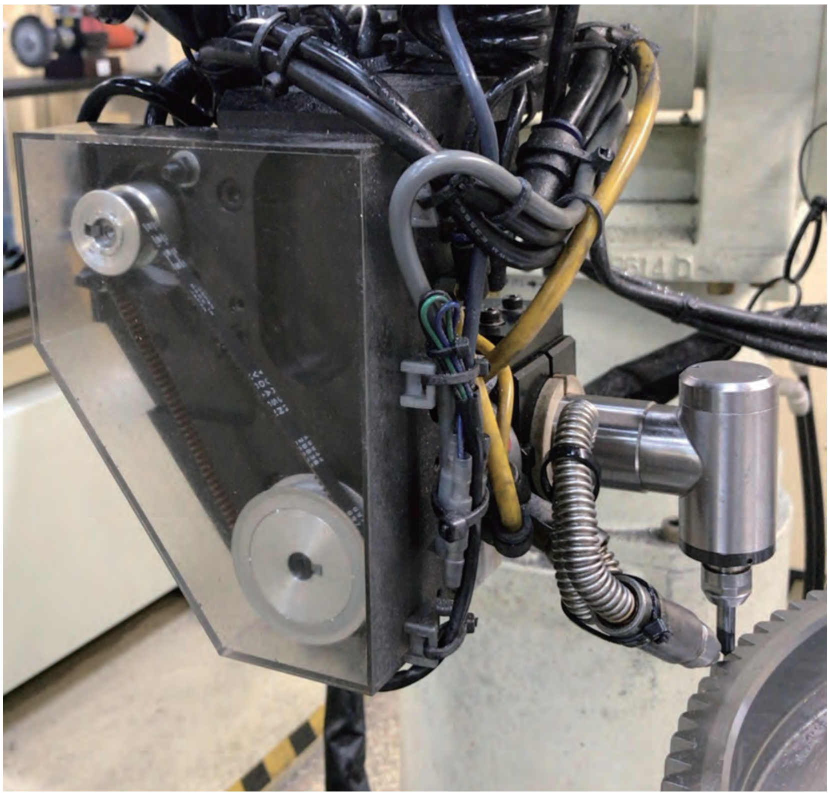


Fig. 7 Constant-pressure device with touch sensing system

that are one meter or larger in diameter and housing components can also be realized by coordinated actions of robots and rotary tables and centering-less technology. Moreover, volume-production processing is now occurring for tip finishing of high-hardness steel gear components by applying carbide cutting tools and belt sanders.

In the future, the applications will expand not only to edge-finishing processing, but also to polishing aimed at reducing surface roughness of blisk-shaped components and assembling gearboxes. The technology also holds promise for other fields such as loading/unloading of works to and from processing machines.

Conclusion

By capitalizing on our company's strengths of having in-house units to develop and produce robots to manufacture aircraft fuselages and engines, we are not only developing robots suitable for production, but are simultaneously creating production technologies with company-wide synergy by taking advantage of robot control and manufacturing technologies.

The aircraft field is an industry what will grow in the future, but competition will continue to intensify, so to expand the business we need to promote cost reductions while satisfying quality requirements. For this purpose, robot-centered automation is paramount. In this light, we will strive to reduce costs associated with quality improvement by capitalizing on the company's strengths in developing robots and systems, as well as manufacturing processes.

Reference

1) H. Okada, K. Kamimuki, S. Yoshikawa, S. Fukada: "Refill Friction Spot Joining for Aerospace Application," SAE Technical Paper 2015-01-2614 (2015)
2) Kitamura, Koyama, Horiuchi, Irie and Kinoshita: Ultra-Heavy Weight Transportable High-Rigid Robot "MG10HL" and Production of Aircraft Components by Using MG10HL, Kawasaki Technical Review, No. 178, pp. 14-17 (2017)
3) Patent No. 6182280, "Friction Spot Joining Tool and Friction Spot Joining Method"

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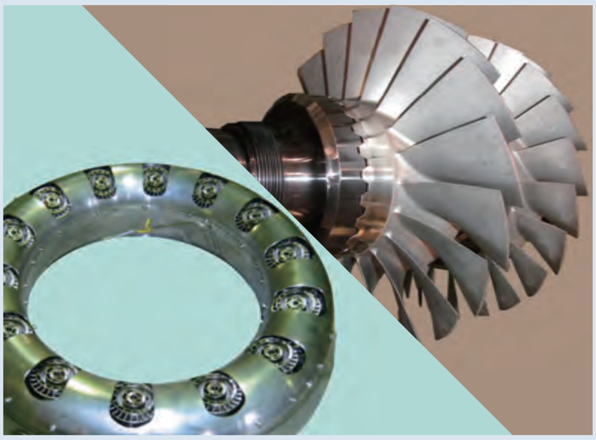
Technology Development of Compressor and Combustor for Performance Improvement of Aircraft Engine



Civil aircraft engines are expected to have excellent economic and environmental friendliness to address the rapid increase in air transportation and global warming due to global economic growth. We are developing technologies for future aero-engine components.

We have developed design methodology for high efficiency compressor for better fuel consumption, and lean staged combustor for NOx reduction. We are continuously working on improving the component testing and the numerical analysis for further development.

Introduction

To address the rapid increase in air transportation due to global economic growth and global warming, there is increasing demand for economical engines which can be met by measures such as lowering fuel consumption and for environmental friendliness by measures such as reducing NOx in the exhaust gas.

Under such a situation, the demand for better performance aircraft engines is high and the market is expected to expand in the near future.

1 Background

We are currently involved in the business of aircraft engines by participating in international joint-development programs and conducting research and development to enhance our market share. Specifically, we are working to improve proprietary technologies for compressors and combustors.

2 Technical Challenges in Developing Aircraft Engines

Figure 1 shows the basic components of a typical aircraft engine such as a compressor that compresses air, a combustor that burns the fuel, and a turbine that extracts power from the high-temperature, high-pressure combusted air.

In the development of each component, a phased performance evaluation is required before incorporating it into an engine. **Fig. 2** shows the technology readiness level (TRL) of component development for combustor. Our research and development activities are aimed at acquiring level-5 technologies of TRL definition that can help reduce fuel consumption and NOx emissions.

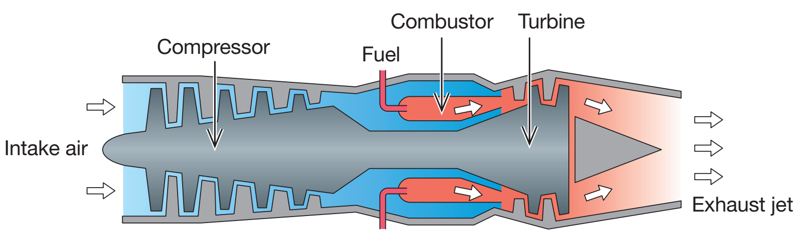


Fig. 1 Schematic of an aircraft engine

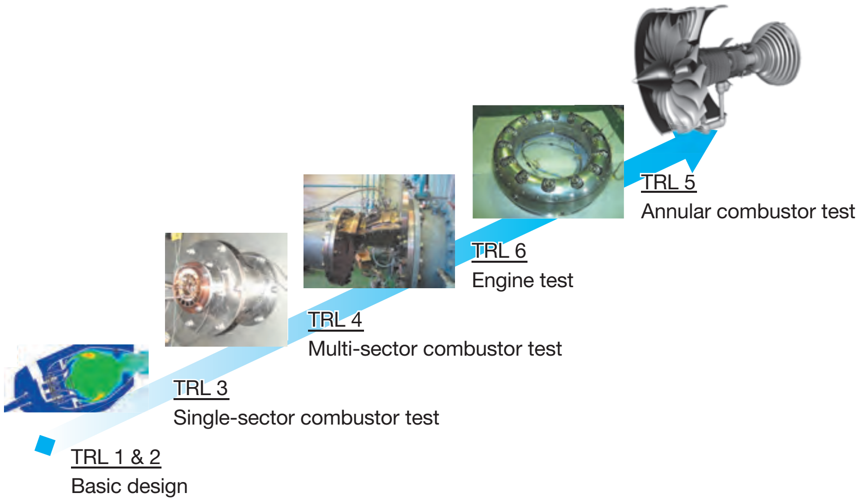


Fig. 2 Technology readiness level (TRL) of combustor

(1) Technical Challenges in Reducing Fuel Consumption

To reduce fuel consumption, each engine component needs to become lighter and more efficient. A compressor comprises multiple stages of rotating blades that rotate at high speed and of stationary vanes. For higher efficiency, we need to design an airfoil shape with lower losses. However, the load on airfoil tends to increase by reducing the number of stages for a lighter engine.

On the other hand, for safe engine operation, the compressor needs to have a sufficient operating range to avoid unstable compressor operations such as surge or stall.

In developing a compressor, the major challenge is realizing a design to maintain balance between weight, efficiency and operating range.

(2) Technical Challenges in Reducing NOx

Aircraft engines produce NOx in the combustors, where the air temperature is the highest in the engines. NOx emissions increase exponentially with combustion temperature; therefore, reducing the combustion temperature is important for NOx reduction.

In response to this issue, we are developing a lean staged combustor[1)] as a combustor that could operate at lower combustion temperature, compared with a conventional one by lowering the ratio of fuel to air as shown in **Fig. 3**. In addition, the combustor is expected as a next-generation combustor since it can significantly reduce particle matters as well as NOx. On the other hand, there are still many technical issues surrounding its implementation such as stability, combustion efficiency and possible damage to the combustor caused by auto-ignition, flashback or combustion oscillation.

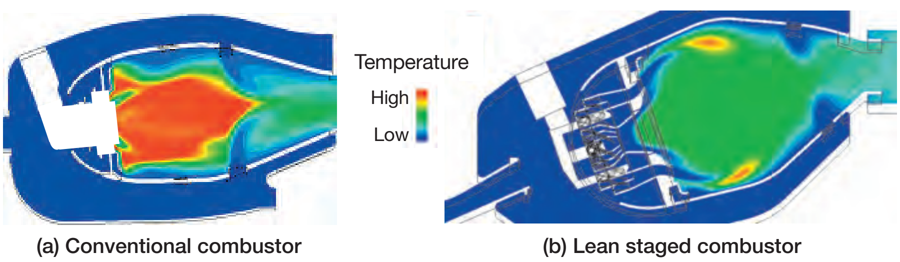


Fig. 3 Temperature distribution of combustor

The first step toward reducing NOx, the important issue in developing a lean staged combustor, is forming a uniform premixed fuel-air mixture.

3 Approaches to Reducing Fuel Consumption and NOx

(1) Reducing Fuel Consumption

As an approach to reducing fuel consumption, we have developed an airfoil design system and demonstrated its effectiveness in compressor testing. In addition, we are working on enhancing our numerical analysis technologies to simulate the experimental results more accurately.

(i) Airfoil Design System

In designing airfoils these days, it is common practice that design is performed in parallel with checking various performance characteristics of the airfoil using computational fluid dynamics (CFD). However, a lot of trial and error is needed to select an optimal set of parameters from a broad range of design parameters. To perform such tasks efficiently and accurately, we have built a system that can automatically select a most suitable set of design parameters by using a genetic algorithm as shown in **Fig. 4**. The optimization of aerodynamics and that of vibration and stress were separately conducted in the past, but this system allows them to be performed simultaneously. **Figure 5** shows a comparison of pressure loss distribution in the radial direction for a new type of airfoil designed by this system and a conventional airfoil. This process makes it possible to design efficient airfoils with lower total pressure loss compared with conventional airfoils.

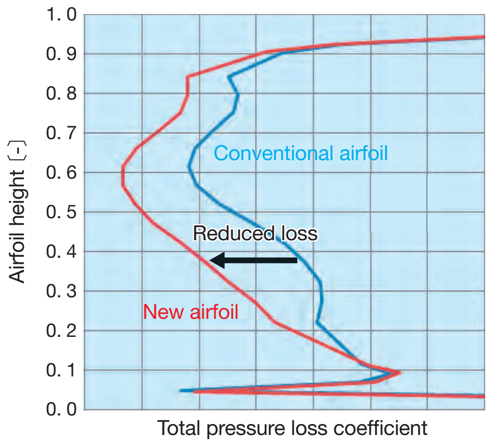


Fig. 5 Distribution of total pressure loss

(ii) Compressor Testing

The newly designed airfoils are verified through compressor testing. The testing was performed on a two-stage axial-flow compressor, the equipment for which is shown in **Fig. 6**. Compressor testing enabled us to assess aerodynamic characteristics such as pressure ratio and efficiency as well as vibration characteristics to confirm mechanical integrity. In addition, the stall or surge

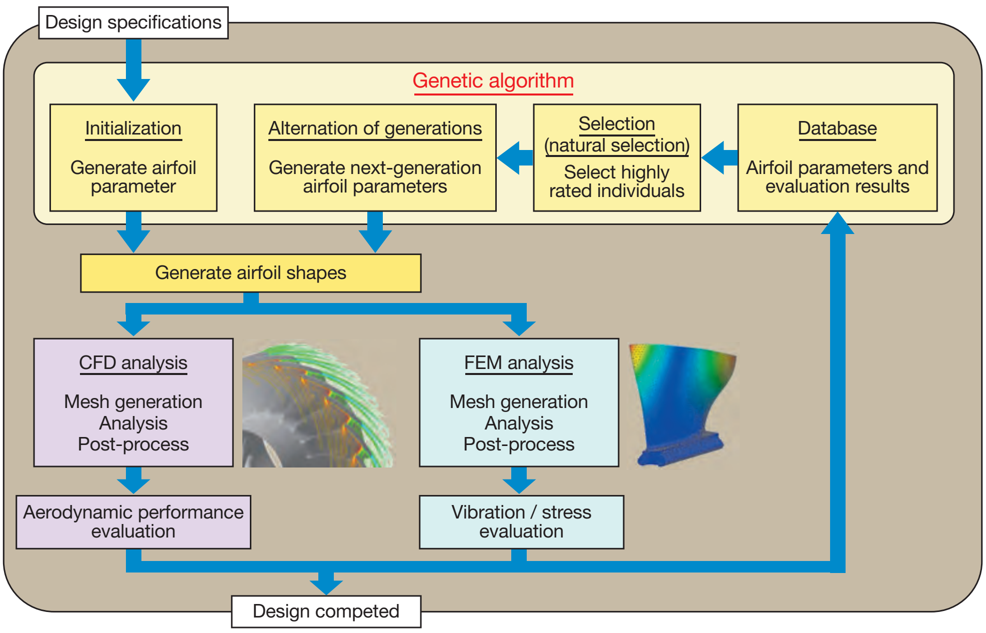


Fig. 4 Airfoil design optimization system

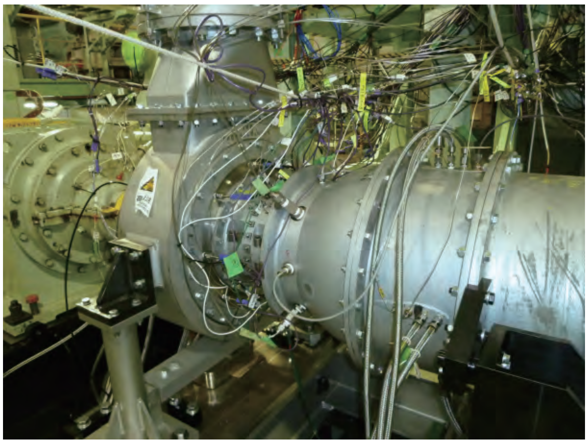


Fig. 6 Compressor test rig

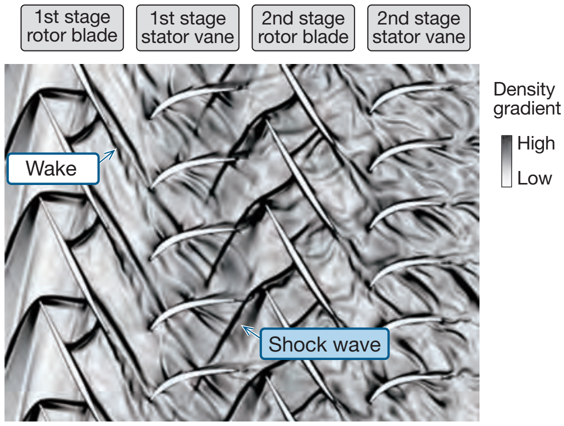


Fig. 7 Density gradient distribution in blade-to-blade plane

conditions were also verified, which are difficult to predict in the design phase.

(iii) Numerical Analysis

In designing airfoils, steady computation with time-average of the flow field is generally used due to the time constraints for analysis. However, as steady computation cannot precisely capture the rotor-stator interactions in a multi-stage compressor, the instability phenomenon such as surge cannot be predicted accurately. Consequently, we are conducting research on unsteady computations with higher time accuracy.

Since unsteady computation is a larger-scale analysis compared to steady computation, we are conducting a collaborative research with Kyushu University using the supercomputer "K computer"[2). The research is being carried out on the two-stage compressor for which the compressor testing was conducted. The density-gradient distribution near the airfoil tip is shown in **Fig. 7**. Similarly, a complex flow can be captured in which wakes and shock waves from airfoils interfere with adjacent airfoils.

(2) Reducing NOx

Many combustors for aircraft engines are of the annular type in which the fuel injected from circumferentially placed burners is burned in the annular combustion chamber located downstream, as shown in the representative figure.

In a lean staged combustor, the fuel and air are premixed in the burner before being burned in the combustion chamber. It is important to improve the burner performance because the more uniform the premixed fuel-air mixture is, the less NOx produced.

In developing the burner, we are conducting joint research and development with the Japan Aerospace Exploration Agency (JAXA) to address issues such as creating uniform premixed fuel-air mixture flames, visualizing the air-flow field, fuel distribution and combustion by using numerical analysis and optical measurements to gather data for combustor design. For the combustor designed, we evaluate its performance through high-temperature, high-pressure combustion testing. There are few places in the world where annular combustion testing for engines with increasingly higher compression ratios can be performed under conditions close to the actual temperature and actual pressure. However, as shown in **Fig. 8**, we have access to JAXA's large-scale, high-temperature and high-pressure combustor test rig to conduct performance evaluations under conditions as close to the actual temperature and

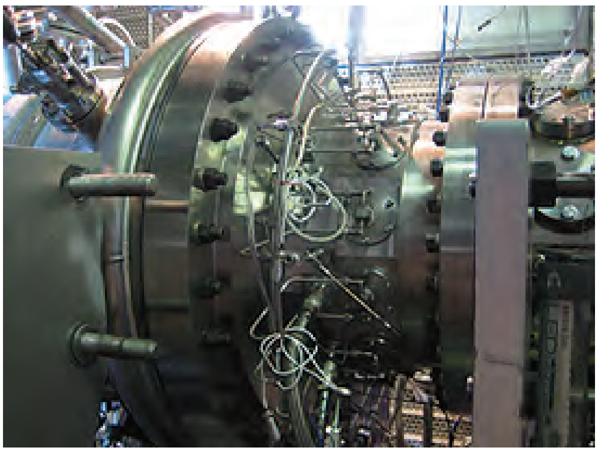


Fig. 8 High temperature and high-pressure combustor test rig

actual pressure as possible, enabling us to evaluate the performance more accurately.

(i) Premixed Fuel-Air Mixture Flames

Figure 9 shows flames from the burner for different premixture levels during the combustion testing. The red circular region is an area where the cylindrical facility is red-heated, the blue region is flames, and the horizontal bar in the center is a probe for measuring exhaust gases.

Figure 9 (a) shows the case where the premix is not uniform and the flames form streaks in the circumferential direction, while **Fig.9 (b)** shows the case where the premix is uniform, and the flames form evenly in the circumferential direction. Furthermore, NOx emissions are significantly reduced when the premix is uniform[3]. To make the premix uniform, we need to accurately determine the air-flow field and fuel distribution.

(ii) Numerical Analysis

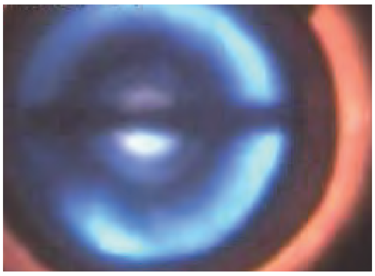
We use numerical analysis for capturing the air-flow field. Numerical analysis is effective for understanding the premix, large air-flow field in the combustor that affects ignition and stability performance as well as outlet temperature distribution, the air-flow separation and velocity distribution in the burner involving risks of auto-ignition and flashback (**Fig. 10**). Particularly for the latter, a more detailed and a larger-scale analysis is needed to precisely reproduce the shape of the computed object, and the analysis is being performed at JAXA by using the non-combustion analysis code UPACS (Unified Platform for Aerospace Computational Simulation) and a supercomputer.

(iii) Optical Measurement

Figure 11 (a) shows a visualization test of fuel spray distribution within a burner in a high-pressure condition. By making the outermost part of the burner transparent, we can visualize the fuel spray distribution in a burner. In addition, using a laser technique makes it possible to obtain more detailed information such as fuel-droplet size and velocity of the visualized burner.

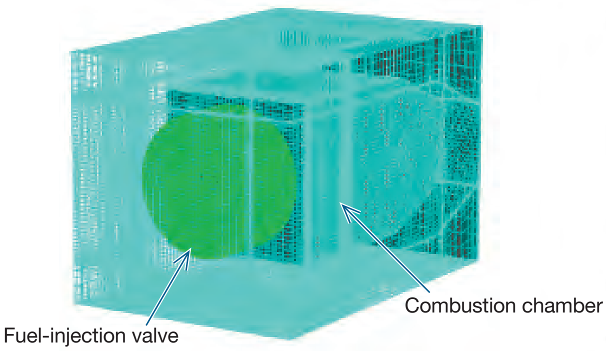
Figure 11 (b) shows flames during combustion testing of a burner. Using a glass-walled combustion chamber for

(a) Flames when premix is not uniform

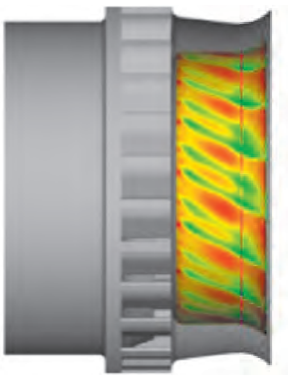


(b) Flames when premix is uniform

Fig. 9 Premixed flame



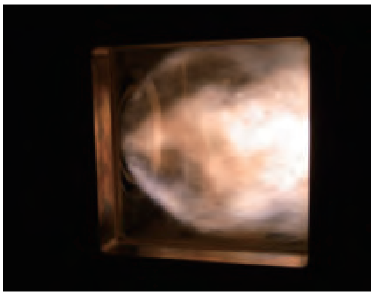
(a) Model external view



(b) Velocity distribution in the fuel-injection valve

Fig. 10 CFD in the burner

(a) Visualization of fuel spraying



(b) Visualization of combustion

Fig. 11 Visualization of the interior of combustor

the test makes it possible to view the combustion status. With optical devices such as a laser, together with visualization, information such as fuel spray distribution, vapor fuel distribution, and combustion can be obtained more in detail.

Conclusion

We are working on improving the technologies for compressors and combustors towards implementing these technologies in future civil aircraft engine business. We will continue developing technologies and proposing activities to engine developers (OEM) henceforth.

Part of this research is the result of our joint study with Kyushu University and JAXA, including an adopted subject for the use of the Research Organization for Information Science & Technology's HPCI system. We express our gratitude to the people involved in this research.

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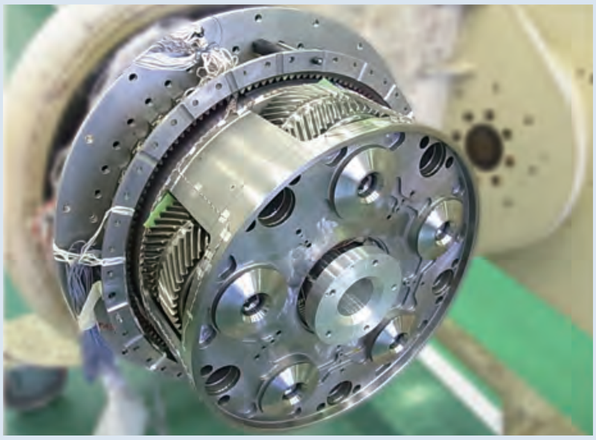
Reference

1) Patent No. 5988261 "Fuel Injector"
2) S. Saito, K. Yamada, M. Furukawa, K. Watanabe, A. Matsuoka, N. Niwa, "Flow Structure and Unsteady Behavior of Hub-Corner Separation in a Stator Cascade of a Multi-Stage Transonic Axial Compressor," Proceedings of ASME Turbo Expo 2018, June 11-15, 2018, GT2018-76480
3) R. Matsuyama, M. Kobayashi, H. Ogata, A. Horikawa, Y. Kinoshita: "DEVELOPMENT OF A LEAN STAGED COMBUSTOR FOR SMALL AEROENGINES," Proceedings of ASME Turbo Expo 2012, June 11-15, 2012, GT2012-68272

Advancement of Aircraft Gear Box Design Technology



It is necessary to reduce the weight and enhance the reliability and efficiency of aircraft gear boxes to satisfy recent severe demands for improving the aircraft's fuel efficiency and reliability. We have developed and manufactured a variety of aircraft gear box products and developed world-leading design technologies through analysis and simulation leveraging CAE technology.

Introduction

Amid the issues of global warming and fuel price hikes, the aircraft industry is facing more and more intense demands for increase in fuel efficiency, reduction in greenhouse gas emissions, and enhanced reliability. In addition, the number of flights is increasing in line with passenger growth, as is maritime transportation by helicopters mainly to oil rigs in the ocean, which is raising demand for safety improvements.

1 Background

The market for aircraft is anticipated to steadily grow also in the future. Not only will aircraft gear box products for them need to be more lightweight, reliable, and efficient, but competitively priced new models will have to be put to market as quickly as possible. This situation requires short-term and low-cost product development.

2 Design problems with aircraft gear boxes

We are the world's leading aircraft gear box manufacturer that conducts development, manufacture, repair, and overhaul of various products as shown in **Fig. 1**: the transmission for helicopters such as BK117, the accessory gear box for aircraft engines, and the constant-frequency power generator for aircraft (T-IDG), which is based on the mechanism of traction drive CVT (continuously variable transmission). Recently, there has been progress in the development of aircraft geared engines[1)], such as geared turbofans, that operate fans via gears. We are also developing gear boxes for these engines.

Our aircraft gear boxes have been designed based on past achievements and experience. We based designs on repeated prototype test results, design changes, and retests until a final design emerged. This trial-and-error method took a long time and was expensive. However, gear box products for the next-generation aircraft need to be developed faster and at lower cost than ever before. They must also be lighter, more reliable, and more efficient, as well as being safer. In this light, we have needed to develop an efficient design method that meets customers' requirements in as little time as possible.

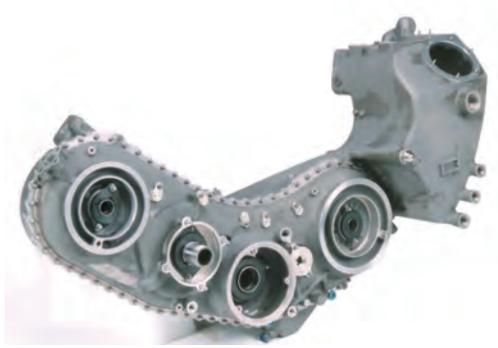
3 Efficient design method using CAE technology

To solve these problems, we developed a new design method that combines knowledge from past achievements and experience and simulation analysis that uses the latest CAE technology, and verified this method with tests. This method estimates the deformation and temperature of each component when creating designs to improve reliability, as well as predict the amount of loss to increase efficiency.

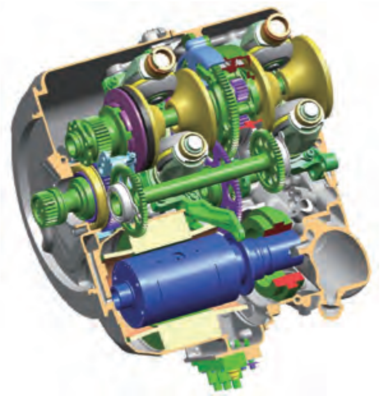
(1) Reducing misalignment by analyzing gear box deformation

Misalignment occurs due to deformation of components to

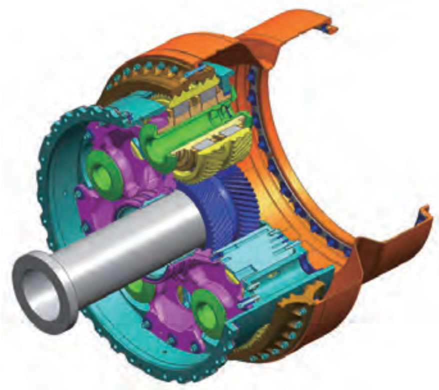
(a) Transmission for BK117



(b) Accessory gear box for aircraft engines



(c) T-IDG



(d) Gear box for geared engines

Fig. 1 Representative KHI aircraft gear box

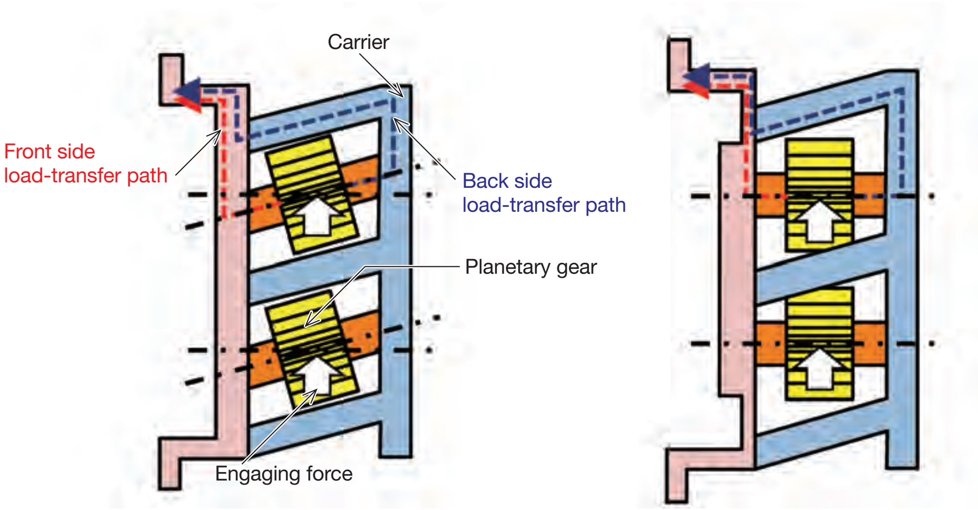
which a load is applied, resulting in non-uniform contact on gear teeth and bearing contact surfaces, reducing gear box reliability. Improving gear box reliability required reducing the misalignment. Although increasing the stiffness of a component by increasing its thickness can suppress deformation, it also increases weight. To solve this problem, we have developed a design method[2)] that reduces the misalignment and reduces the weight at the same time by calculating the deformation of each component using a finite-element FEM analysis and adjusting the stiffness of each component.

As **Fig. 2(a)** shows, under the conventional design of a planetary gear system, there are differences in stiffness between the front and back sides of the load-transfer path by torque. This causes the carrier to experience torsional deformation that results planetary gear axis to tilt. In contrast, as shown in **Fig. 2(b)**, the newly developed stiffness optimization design optimizes the stiffness of the load-transfer path to suppress the tilt of the planetary gear axis.

Figure 3 shows the results of the deformation analysis on the misalignment-reducing design. The initial configuration had a front plate with high stiffness, and applying a load caused a large tilt of the planetary gear axis. The optimal configuration, however, has a uniform stiffness both at the front and back sides of the load-transfer path, which achieves reduction in the tilt of the planetary gear axis and a lightweight gear system. We built a practical-sized test unit using this design method to carry out an endurance test simulating practical operational conditions. The results of the teardown inspection after the endurance test revealed that the main structural components, gear teeth surfaces, and bearings were all in a sound condition, which demonstrated the effectiveness of this design method[3)].

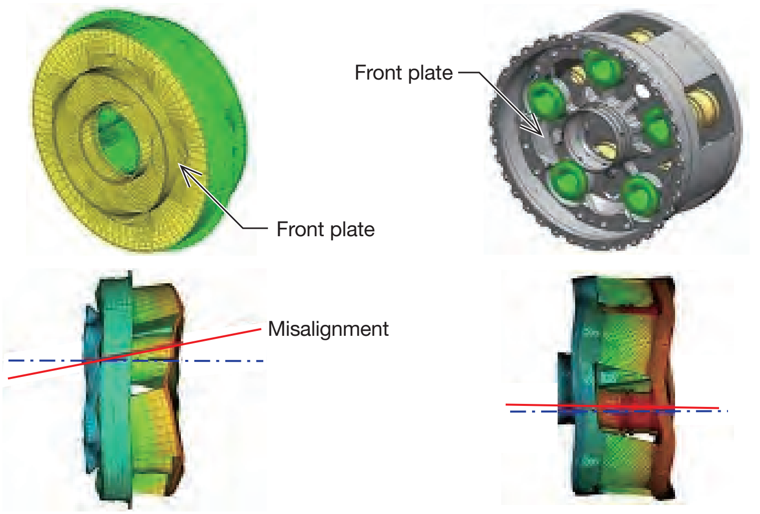
(2) Optimization of tooth contact taking into account deformation of components

To make the high-reliability bevel gears used in aircraft gear boxes, the contact of the tooth surface (tooth contact



(a) Conventional design (b) Optimally designed stiffness

Fig. 2 Design of planetary gear system



(a) Initial shape (b) Optimally designed shape

Fig. 3 Misalignment reduction through deformation analysis

pattern and contact stress distribution) that transfers power under various load conditions during operation needs to be optimal. Tooth contact is greatly affected by the deformation of gears and supporting components caused by loads. To reduce deformation, it would be necessary to increase the stiffness of each component; however, that would mean increasing the weight of each component. Therefore, it took a long time to design the best tooth contact that allows lightweight and reliable gears. To carry out quick and low-cost designs for lightweight gears with reduced deformation, we developed a gear tooth surface design method that estimates load-caused deformation of each component and predicts the tooth contact condition by simulation.

Figure 4 outlines the developed design method that optimizes tooth contact conditions. In this method, first,

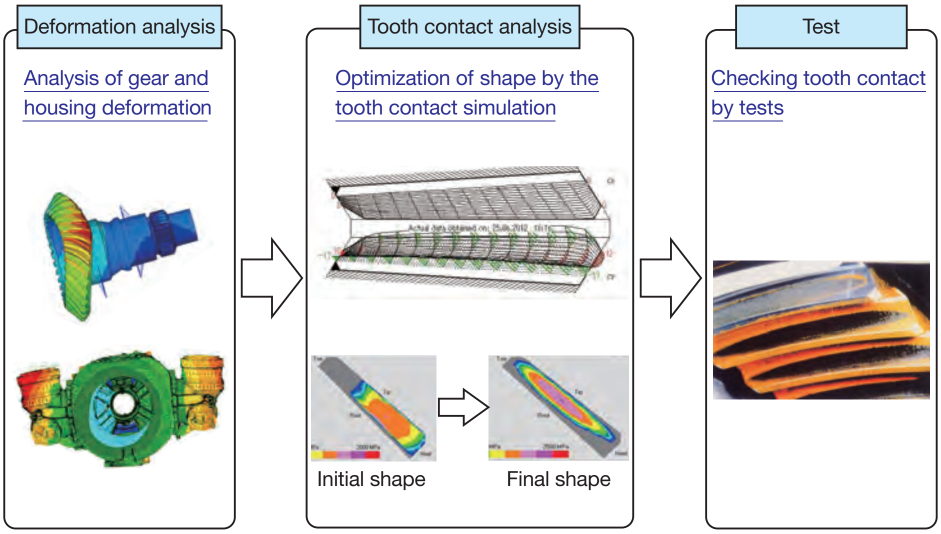
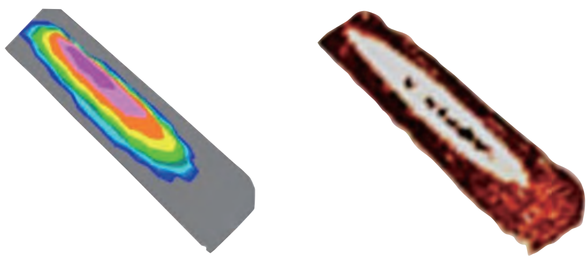


Fig. 4 Gear tooth contact pattern optimization design method

the tooth contact shape and tooth contact position following deformation is predicted after the deformation of gears and components of the gear housing is analyzed by using FEM analysis. Next, the tooth contact condition is analyzed and the tooth contact pattern is optimized by using tooth contact simulation software. After that, we manufacture a test gear and check whether the tooth contact pattern is appropriate by testing.

Figure 5 shows a prediction of tooth contact obtained by this method and a tooth contact obtained by a practical loading test. The gray area in the analysis results in **Fig. 5 (a)** and the brown area in the test results in **Fig. 5 (b)** are one tooth surface, and the central oval area is the tooth contact pattern. These analysis and test results agree well with each other, which demonstrates this design method is effective.



(a) Analysis results (b) Test results

Fig. 5 Analysis and test results of gear tooth contact pattern

(3) Loss reduction by CFD on oil flow

Loss of efficiency in a gear box product is caused by rotational components inside the gear box. The main factors causing energy loss are churning and windage losses in churning lubrication oil and cooling oil, as well as friction loss caused by contact between components.

The oil churning loss is mainly caused by the pumping action of a gear that has a structure like compressor blades and churns the surrounding fluid hard. Aircraft gear boxes use high-speed rotational gears and the oil churning loss often accounts for over 50% of the gear box's total loss. To reduce this loss, the momentum transferred to oil has to be minimized, or appropriate amounts of oil shall be supplied at suitable points, and it shall be immediately discharged.

To create a design with reduced loss, we have developed a completely new CFD simulation technique[4] by appropriately modeling the fast two-phase flow of oil and air as well as the area where gears engage. To reduce bevel gear loss, we applied this technique to a structure that covers gears with shrouds and has an oil discharge outlet, and verified this technique by conducting an estimation/simulation of the oil churning loss and windage loss and carrying out tests.

Figure 6 shows the situation without shrouds, and **Fig. 7** shows the one with shrouds. Without shrouds, oil splashes around inside the gear box and the gears churn it to increase loss. On the other hand, with shrouds, only appropriate amounts of oil flow on to the gear surfaces; moreover, adjusting the oil outlet position can smooth the oil flow inside the shroud to decrease loss. Regarding the

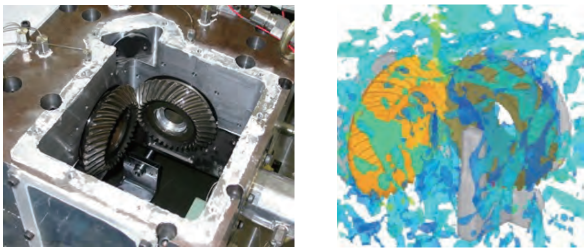


Fig. 6 Test gear box and simulation result (without shroud)

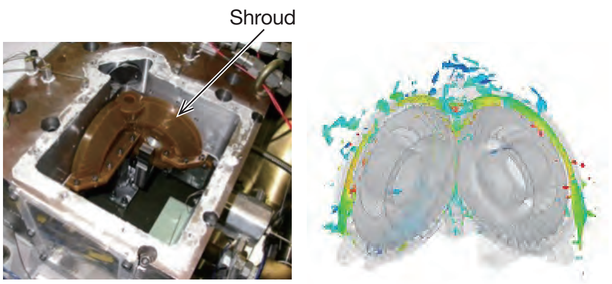


Fig. 7 Test gear box and simulation result (with shroud)

loss reduction ratio when shrouding is in place, the simulation and test results well agree closely with each other, which demonstrates that this technique is useful for optimizing the design to achieve high efficiency. In addition, this test demonstrated that adjusting the shroud shape and the oil outlet position can decrease loss by about 30% compared with the case without shrouds.

This design method was applied to the design of specimens for the planetary gear system verification test. The results revealed that for all the gear box models, the method helped to achieve a transfer efficiency of 99.5% or higher[5], the target efficiency.

(4) Improving the loss-of-lubrication performance by CFD and heat-transfer analysis

One of the safety requirements of helicopters is transmission performance in a loss-of-lubrication state. A loss-of-lubrication means running out of lubrication and cooling oil for gears and bearings. In a loss-of-lubrication state, gears and bearings overheat and seize up, rendering them useless. This may cause an emergency landing or a crash. The loss-of-lubrication performance means the ability to continue flight in a loss-of-lubrication state. A loss-of-lubrication performance of 30 minutes or longer is required today. However, as transportation by helicopters to and from offshore oil rigs is growing, instances of long-distance transportation are increasing, and the next-generation helicopters will need to have loss-of-lubrication performance higher than ever.

Conventionally, in a design for improving loss-of-lubrication performance, sizes of gears and bearings are selected by a rule of thumb, which is based on test data, to delay seizure. It is difficult for a design depending on a rule of thumb alone to obtain higher loss-of-lubrication performance. A new design method is needed.

Figure 8 shows a history of change in bearing temperature after the oil is lost in a loss-of-lubrication test of an actual helicopter gear box. If the lubrication and cooling oil for gears and bearings is lost, the temperature of each part gradually increases to eventually damage the gears and bearings. The temperature rise from the start of the loss-of-lubrication to the finish is roughly categorized into the following three stages: ① the balance between heat generation and heat dissipation is lost due to the oil loss; ② rise in gear temperature caused by seizure; and ③ rise in bearing temperature caused by seizure. In each of these stages, the temperature probably approaches a certain time constant toward the temperature where heat generation and heat dissipation converge.

To evaluate the loss-of-lubrication performance quantitatively at the design stage without depending on past experience or practical machine tests, we are now developing a method for evaluating loss-of-lubrication performance that combines CFD and the heat-transfer analysis based on the estimation described earlier.

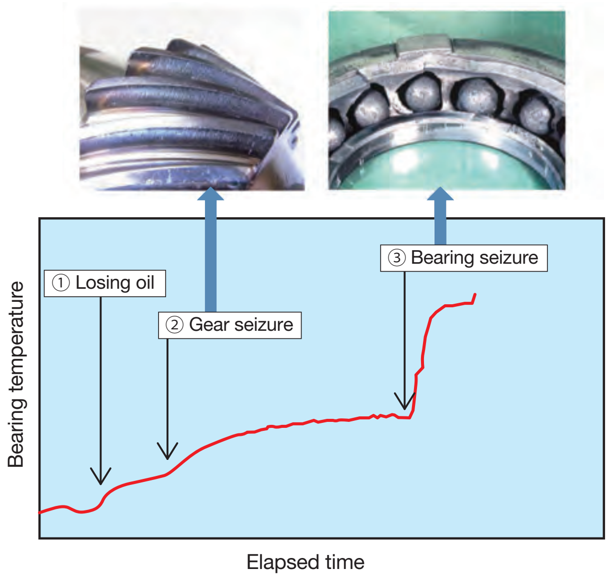


Fig. 8 Loss-of-lubrication test result

Conclusion

Thanks to the recent advances in CAE technology, the front-loading type development based on the optimum design method became available. Meanwhile, aircraft gear boxes are required to be more lightweight, reliable, and efficient than products of other fields. In addition, the recent aircraft market demands short-term and low-cost development of gear boxes.

We will further improve these world-leading design analysis and simulation technologies, and apply them to the designs of practical machines as well as developing new design technologies. Based on these technologies, we plan to promote differentiated products and increase market share, and thus aim to become a world-leading manufacturer of aircraft gear products.

Reference

1) Goi, T., “The Overview on the 'Geared' Aeroengines,” Journal of Gas Turbine Society of Japan (in Japanese), Vol. 43, No. 3, 2015.5
2) Matsuoka, T., et al., “Light Weight and Low-Misalignment Planetary Gear System for Open Rotor Power Gearbox,” ASME IDETC/CIE 2011, DETC2011-47342
3) Sato, K., et al., “Design, Analysis, and Tests of Differential Planetary Gear System for Open Rotor Power Gearbox (Final Report),” ASME IDETC/CIE 2015, DETC2015-46414
4) Arisawa, H., et al., “CFD Simulation for Reduction of Oil Churning Loss and Windage Loss on Aeroengine Transmission Gears,” ASME GT 2009, GT2009-59226
5) Imai, H., et al., “Design and Test of Differential Planetary Gear System for Open Rotor Power Gearbox,” ASME IDETC/CIE 2013, DETC2013-12089

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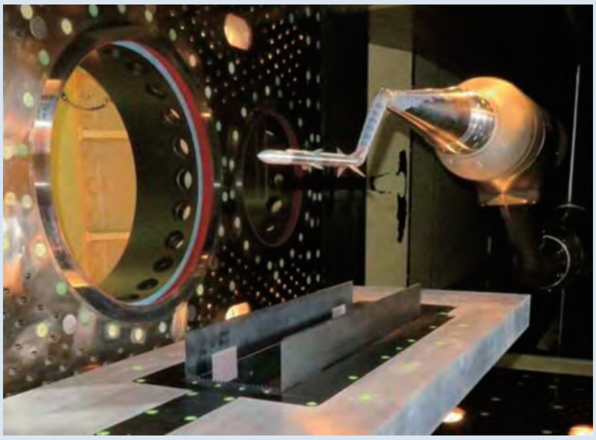
Evaluation of Store Separation Characteristics from Aircraft Using Aerodynamic Technology



The latest military aircraft is equipped with stores in the internal weapon bays to improve stealth and speed performance.

In this context, we developed a store separation characteristics evaluation system to analyze the flow-fields of the subsonic to supersonic ranges and simulate them at the wind tunnel test to identify the flow around the internal weapons bay and how the store is separated from the aircraft in flight for the first time in Japan. This system has been integrated into the Tri-sonic Wind Tunnel in the Chitose Test Center of the Acquisition, Technology & Logistics Agency.

Introduction

One purpose of military aircraft is to carry and drop stores such as missiles and bombs in flight. If stores are attached to the bottom of the fuselage or underwing hardpoints, however, they reflect radar signals and generate aerodynamic drag resulting in decrease stealth and speed performance. To avoid this problem, many of the latest military aircraft feature an internal weapons bay that houses stores to improve performance.

1 Background

When the weapons bay door is opened, it exposes the concavity of the internal weapons bay and generates a cavity flow, which is a complicated air-flow pattern, around the bay. A cavity flow varies greatly in flow velocity and pressure, and ever-changing aerodynamic forces are exerted on stores that pass through this flow. Moreover, cavity-flow conditions for subsonic flight speeds often differ from those for supersonic speeds. Therefore, as the aerodynamic forces on stores vary by flight speeds, it is important to predict trajectories on release from the internal weapons bay.

2 Store separation from aircraft

When a store is separated from an aircraft, there is a risk that it may rise due to aerodynamic force to hit the aircraft. To prevent such accidents and secure safe flights, it is essential to verify the store separation characteristics before flight. For this purpose, the CFD (computational fluid dynamics) analysis is used in addition to a wind tunnel test such as the CTS (captive trajectory system) test.

The MPA (maritime patrol aircraft) P-1, shown in **Fig. 1**, has an internal weapons bay that keeps stores in the fuselage. When using an internal weapons bay, the P-1 flies at a relatively low speed, while fighters fly at transonic or supersonic speed. As **Fig. 2** shows, an air-flow layer called the shear layer, forms between the slow air flow in the internal weapons bay and the fast air flow outside the aircraft. In addition, in the velocity range from transonic to supersonic speeds, the flow field becomes complicated as

Fig. 1 Example of internal weapons bay (P-1)

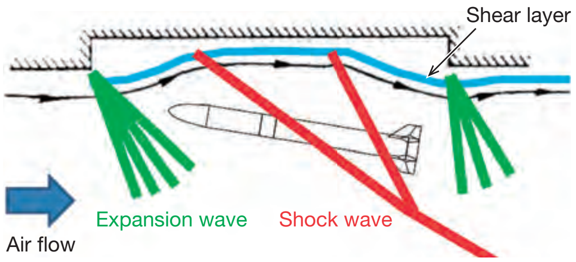


Fig. 2 Example of air flow around internal weapons bay

it involves shock waves and expansion waves, and no analysis of cavity flows with stores has been carried out in Japan until today.

While low speed wind tunnels are available in Japan and have to date been used for store separation tests, overseas facilities had to be used for transonic and supersonic velocities.

3 Technological challenges related to evaluation of store separation characteristics

To evaluate store separation characteristics in the transonic and supersonic speed ranges, as shown in **Fig. 3**, one needs to understand the aerodynamic phenomena and conduct store separation tests using a wind tunnel.

(1) Understanding the aerodynamic phenomena

To separate stores from the internal weapons bay safely, it is important to understand the aerodynamic phenomena around the bay[1].

At transonic and supersonic speeds, as shown in **Fig. 2**, when the supersonic flow along the aircraft is distorted by the internal weapons bay, expansion waves and shock waves occur. Also, a shear layer forms between the flows inside and outside the bay, around which occurs an unsteady flow that varies greatly with time. When a store separates from the internal weapons bay and enters this unsteady flow, the store may change its behavior and hit the aircraft. Therefore, to separate stores safely when flying at a transonic or supersonic speed, it is necessary to understand the aerodynamic phenomena around the internal weapons bay that affect store behavior. However, no-one has addressed this issue up to the present in Japan.

(2) Wind tunnel test of store separation

Although CTS are available in Japan for tests in a range from low to high subsonic speeds, few of them have

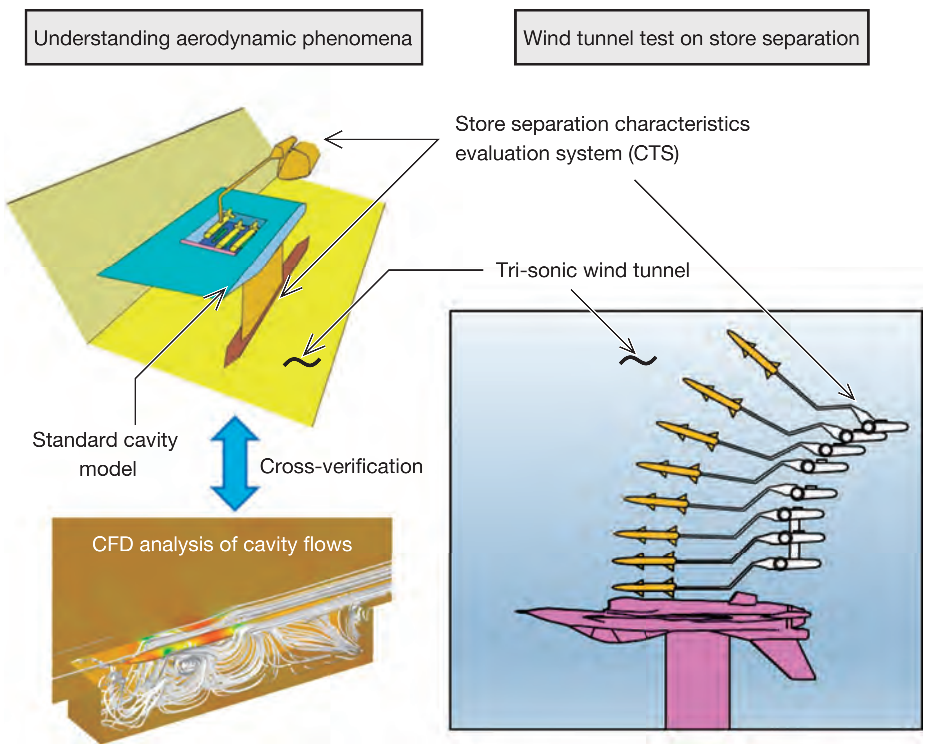


Fig. 3 Concept of store separation characteristics evaluation

conducted simulations on separating stores from the internal weapons bay.

To secure high-quality test results when evaluating store separation characteristics in the transonic and supersonic speed ranges, the most appropriate facility is the Tri-sonic Wind Tunnel[2] at ATLA's (Acquisition, Technology & Logistics Agency) Chitose Test Center. This facility is capable of generating air flows equivalent to those of real flights (a wide Mach range and high Reynolds number). This tri-sonic wind tunnel, which covers a wide range from low to supersonic speeds, needed the development of a CTS that can be used for simulating separation of stores.

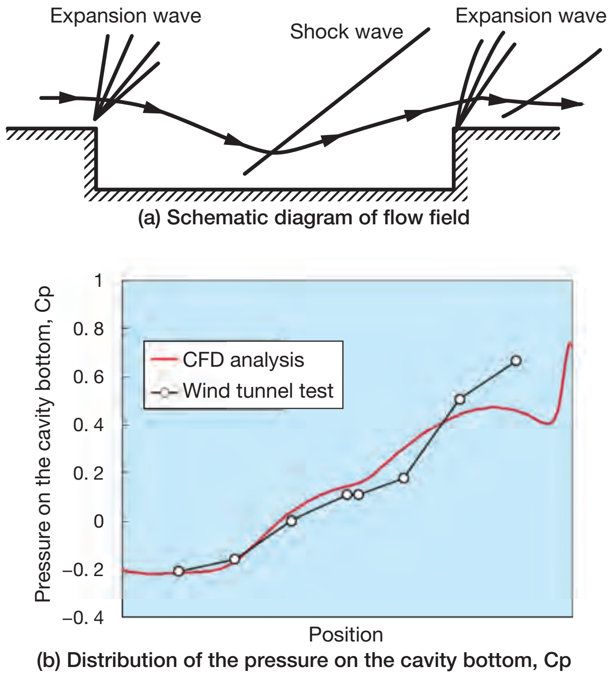


Fig. 4 Example of cavity flow (transitional type, Mach 2.0)

4 Technological development related to evaluating store separation characteristics

(1) Understanding aerodynamic phenomena

(i) Development of a cavity-flow analysis tool

To acquire basic data on cavity flows in the wind tunnel test, we fabricated a model simulating an internal weapons bay and created a CFD analysis tool, and then carried out cross-verification between the analysis and the wind tunnel test data.

We designed and fabricated a standard wind-tunnel model for studies of cavity flows. This model is designed to form a uniform flow over a plate that simulates the fuselage surface around an aircraft's internal weapons bay. In this model, a cavity with a range of depths and lengths is placed to simulate various internal weapons bays, and measured pressure[3].

In creating the CFD analysis tool, we applied the grid-generation technique nurtured through the development of aircraft such as the P-1 to analyze complicated shapes of internal weapons bays and stores. This CFD analysis tool consists of grid data that work on FLUENT, commercial CFD analysis software, and a file for setting calculation conditions. This tool's accuracy has been improved through several wind-tunnel tests[4].

(ii) Cavity flows, which are sensitive to cavity dimensions and the Mach number, are difficult to predict or simulate aerodynamically.

Cavity flow fields are categorized into three types: the open type, the closed type, and the transitional type, which is classed between the former two. They are known to represent different pressure distributions on the cavity's bottom surface.

Figure 4 shows a schematic diagram of a transitional-type flow field and an example of its average pressure distribution on the cavity bottom surface obtained by the CFD analysis and the wind-tunnel test.

The diagram shows that as an air flow runs from upstream of the cavity an expansion wave occurs when the air flow turns around the leading edge of the cavity and then changes direction to enter the cavity. The air is compressed inside the cavity to generate a shock wave, which changes the air-flow direction, and the flow leaves the cavity. At this point, an expansion wave occurs at the trailing edge of the cavity, and the air flow changes direction to downstream. The average pressure distribution on the cavity bottom surface shows that the expansion wave accelerates the flow velocity at the leading edge of the cavity to make the pressure on the cavity bottom, Cp, negative. After that, the flow is compressed by the shock wave to increase Cp downstream.

We compared the three flow-field types for the CFD analyses results and the pressure distribution obtained from the wind tunnel tests, and then confirmed the CFD analysis could predict cavity flow fields.

(iii) Evaluating the effect of leading-edge devices

We conducted an investigation on control capability of the cavity flow by the leading-edge devices shown in **Fig. 5**. Without a leading-edge device, as **Fig. 6 (a)** shows, the shear layer enters the cavity to form a transitional-type flow field. On the other hand, **Fig. 6 (b)** reveals that a leading-edge device deflects the shear layer. In this case, the flow field is the open type, which definitely differs from that in the former case. This difference in shear-layer positions also appears in the total pressure distribution, and both the

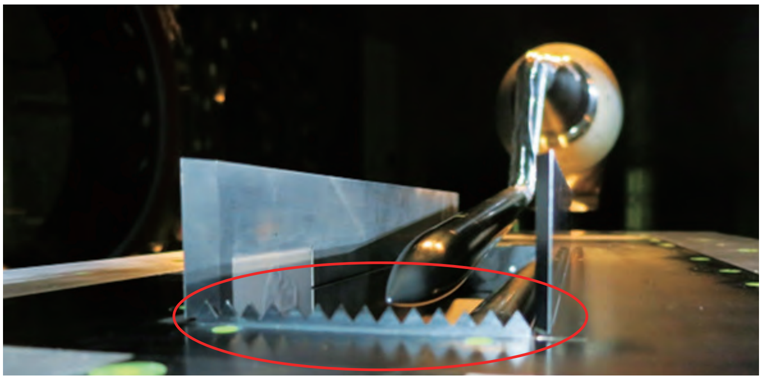


Fig. 5 Shape of leading edge device

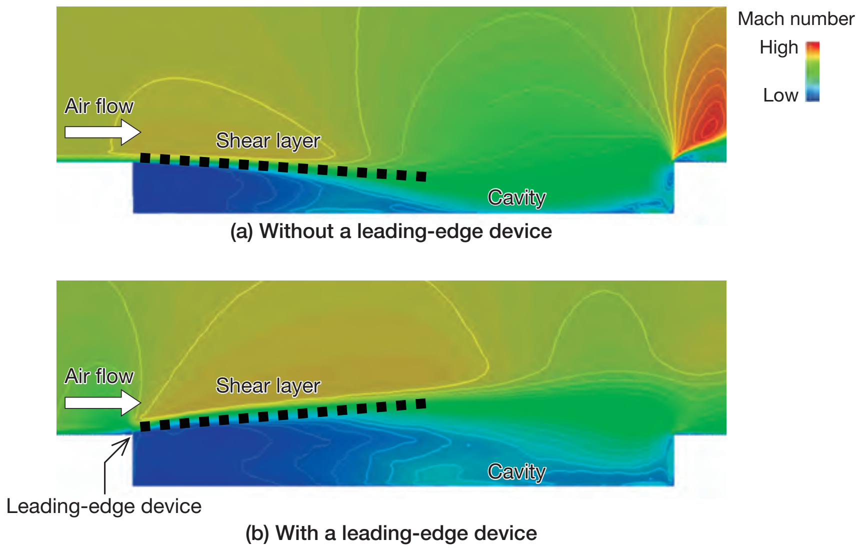


Fig. 6 Effect of leading edge device on cavity flow (Mach contour, free stream Mach 0.85)

wind tunnel test and CFD analysis data show it as well.

Thus, by verifying the CFD analysis results with the wind tunnel test data, we confirmed its capability to appropriately analyze the flow fields around the internal weapons bay with stores in it.

(2) Wind tunnel test on store separation

In 2003, our company developed the CTS for High-Speed Wind Tunnels for the first time in Japan using our own robotic technology, and introduced it into the transonic wind tunnel at the Gifu Works[5]. We used this system to evaluate the store-separation characteristics at high speeds in the development of the P-1, and nurtured the know-how of system design and the technique for evaluating store-separation characteristics. We applied this know-how and technique to development the CTS for Tri-sonic Wind Tunnels shown in **Fig. 7**.

The CTS for Tri-sonic Wind Tunnel is a CTS with three-axis robotic arm that supports the store model and varies the model's attitude. This system features a slim shape due to an offset rotary-joint mechanism that has one of its three axes inclined, reducing its aerodynamic influence in the wind tunnel. Before introducing this system, we conducted research and performance verification tests[6].

Using this CTS verified that the store-separation tests can be conducted in the speed range of Mach 0.3 to 2.5, assumed for future fighter aircraft. Also, to establish the technique that simulates the separation of stores from an

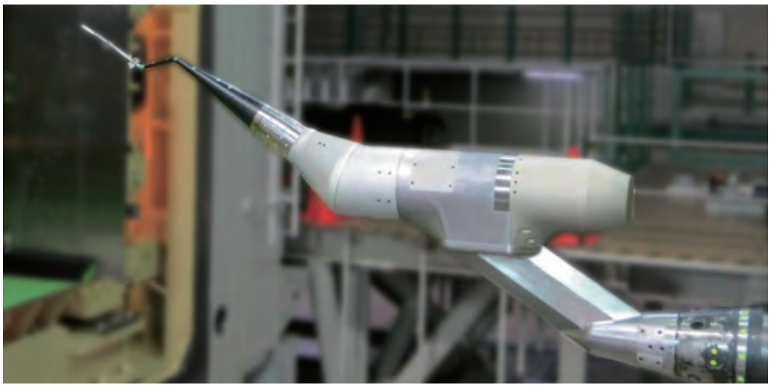
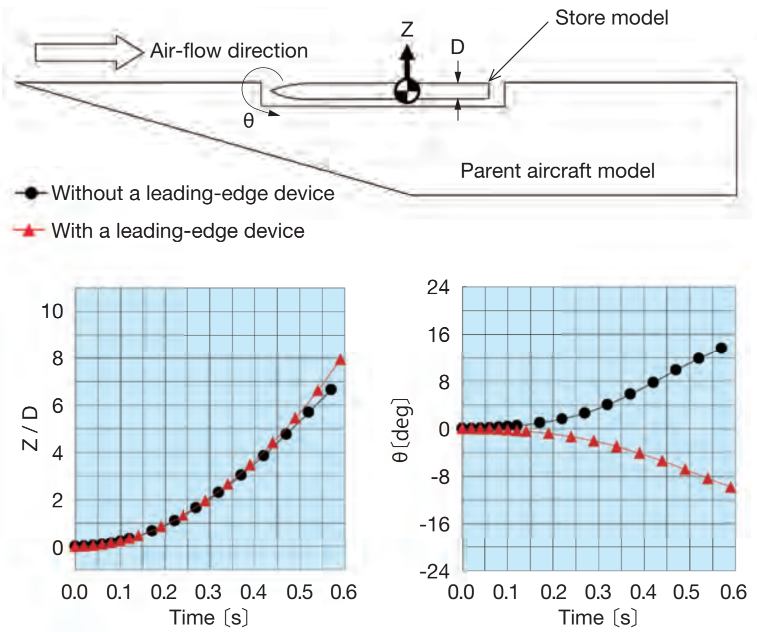


Fig. 7 CTS for Tri-sonic Wind Tunnel



(a) Position in the vertical direction〔Z/D〕 (b) Pitch angle〔θ〕

Fig. 8 Store separation trajectories with or without leading edge device

internal weapons bay, we conducted store-separation tests. These tests used the standard cavity model, and the results showed that it is possible to simulate the separation of a store from its initial position inside the bay for the range covering transonic to supersonic speeds.

Figure 8 shows the separation simulation results with and without a leading-edge device. The difference between shear layer positions due to the presence/absence of the leading-edge device did not affect the vertical positions (Z/D) of the store, whereas it so greatly affected the pitch angle (θ) that the sign was reversed.

Conclusion

By creating a CFD analysis tool that evaluates the air flow around an internal weapons bay, we clarified the aerodynamic phenomena related to cavity flows. This achievement can be applied to R&D for aircraft such as future fighters. In addition, by developing the CTS for Trisonic Wind Tunnels, we became the first in Japan to demonstrate that the system can simulate store separation for flight speeds up to the supersonic range. We plan to use this system to simulate store separation in the development of future aircraft.

This development was conducted as a part of the ATLA's project "Research on the Aerodynamics in and around Weapons Bays." We would like to express gratitude to the Air Systems Research Center for the kind cooperation.

Reference

1) Udagawa, Kikumoto, Sonoda, Ochi, Hashioka, Shirogane, and Kawamura: "Multi-Approach Research on Aircraft Store Separation - Research Program Overview," Proceedings of the 54th Aircraft Symposium (2016)
2) Sugita: "The Development of MOD Trisonic Wind Tunnel," Proceedings of the 45th Aircraft Symposium (2007)
3) Kikumoto, Udagawa, Takao, Sonoda, Suzuki, Kitagawa, Kimura, and Ueda: "Multi-Approach Research on Aircraft Store Separation - Cavity-Flow Wind-Tunnel Test with Internal Stores," Proceedings of the 54th Aircraft Symposium (2016)
4) Ochi, Nagata, Udagawa, Kikumoto, Osawa: "Multi-Approach Research on Store Separation - Comparison between cavity-flow CFD analysis and wind-tunnel test," Proceedings of the 54th Aircraft Symposium (2016)
5) Hamada, Hayama, Ochi, Tsujiuchi, and Suzuki: "Aerodynamic and Aeroacoustic Fundamental Technologies Applied to Aircraft Development," Kawasaki Heavy Industries Technical Review, No. 171, pp. 43-50 (2011)
6) Hashioka, Shirogane, Koyama, Kubota, Tekenaka, Udagawa, Kikumoto, and Kaneko: "Multi-Approach Research on Store Separation - Development of CTS (Captive Trajectory System) for Trisonic Wind Tunnel," Proceedings of the 54th Aircraft Symposium (2016)

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Development of Rescue Operation Support System for Helicopter

To prevent fire-fighting and rescue helicopters from crashing during rescue operations in mountain areas, we have developed a rescue operation support system for helicopters to help the pilot properly recognize risk when hovering during rescue operations or landing on uneven terrain.

We prototyped a system for demonstration and assessment to examine the system, check the man-machine interface, assess the obstruction detection sensor in advance and verify the effects of wireless LAN on the fuselage before starting full-fledged development of the system.

Introduction

Rescue operations with helicopters are effective when it is difficult or takes a long time to reach accident survivors by land or sea. Particularly in Japan, where mountain areas account for 70% of its land, approx. 60% of all rescue operations involving fire-fighting and rescue helicopters are for mountain rescue activities.

1 Background

One type of rescue operation is lifting survivors with a cable extending from a helicopter's hoist as it maintains a fixed altitude and position. While this rescue operation procedure is extremely effective in places without a space to land, there is always a risk of crashing.

After some fire-fighting and rescue helicopters crashed during rescue operations in mountain areas, to prevent recurrence of such accidents the Fire Defense Agency issued the "Study Group Report on Mountain Rescue Methods by Fire-fighting and Rescue Helicopter" in March 2012. In response to this report, each rescue corps clarified flight safety standards such as: (1) increase the number onboard assistants who watch outside the helicopter such as the rear-left area; and (2) when hovering, maintain clearances of 10 m or more in the horizontal direction from obstacles, and 6 m or more from objects below. Some air rescue corps have made it mandatory to operate a helicopter with two pilots on board in all rescue activities. These measures are taken to enhance safety by watching outside the helicopter, and they highlight the difficulties of mountain rescues.

2 Policy for developing a rescue operation support system for helicopters

This rescue operation support system for helicopters presents surrounding-view images (rear-view images in particular), downward-view images, and distance information on surrounding obstacles on a dedicated display unit while hovering during rescue operations or landing on uneven terrain. This reduces the burden on operators by supporting the work of watching nearby obstacles. Our plan is to develop a low-cost system that is easy to install in a helicopter.

(1) Reducing the cost of obstruction detection sensors

Although general aircraft radars can obtain information on obstacles and weather several kilometers away, they are extremely expensive. This system reduces costs by limiting the scope to watching surrounding obstacles when hovering during rescue operations and landing on uneven terrain. Developing this low-cost system is possible by using obstruction detection sensors and cameras developed for automated vehicle operations.

(2) Easy to install in a helicopter

To make it easy to install the system in a helicopter, we minimized wiring by applying a wireless local area network (LAN) system for communication between the dedicated

† Realized the world lowest level of noise in its class, better hovering performance and longer lifetime through adoption of a new tail rotor and other components.

display unit and the computer. Specifically, the system is installed as follows:

- Install a sensor for detecting starboard-side obstacles and a camera for capturing rear-view images on the rear end of the entry step on the helicopter's starboard side; and install a sensor for detecting port-side obstacles and a camera for capturing downward-view images on the rear end of the entry step on the port side.
- Install an image-generating computer and a wireless LAN master unit in the rear of the cabin.
- The dedicated display unit is supposed to be portable; the cockpit is not to be modified.

Figure 1 shows the system configuration, and **Fig. 2** shows a helicopter equipped with these devices.

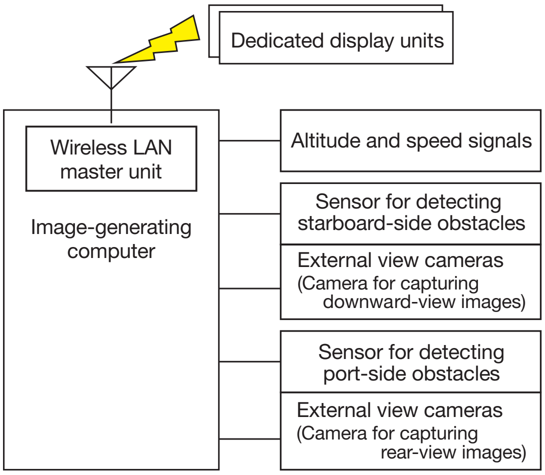


Fig. 1 System configuration

3 Fabricating a prototype system for demonstration and assessment

Before producing a full-fledged version of the system, we developed a prototype for demonstration and assessment. The main pieces of hardware are described below.

(1) Obstruction detection sensors

Obstruction detection sensors detect distances between the helicopter and obstacles as well as their directions. Although it would be ideal to detect all obstacles in the sphere around the helicopter, we assigned priority to securing clearances between obstacles and the main and tail rotors (see **Fig. 2**) and obstacles around the helicopter (particularly in the rear and lateral directions). On an actual helicopter, two obstruction detection sensors would be fitted to the rear of the fuselage, each covering 180 degrees horizontally on each side. To demonstrate and assess the system, however, we attached the sensors beneath a small unmanned helicopter body. The sensor chosen for this purpose was Velodyne's laser radar (VLP-16), which has a coverage range of 360 degrees horizontally. **Table 1** shows its specifications.

(2) External view camera

The external view camera captures images around the helicopter. **Figure 3** shows the camera's video acquisition range. Ideally, it should capture images all around the helicopter (circumferential view) and downward, wide-angle images (bird's-eye view).

For this system, we mounted two web cameras on a small unmanned helicopter. One camera was for rearward views; and another was for bird's-eye views, and they were connected to a computer. This setup evaluated the effect of vibrations.

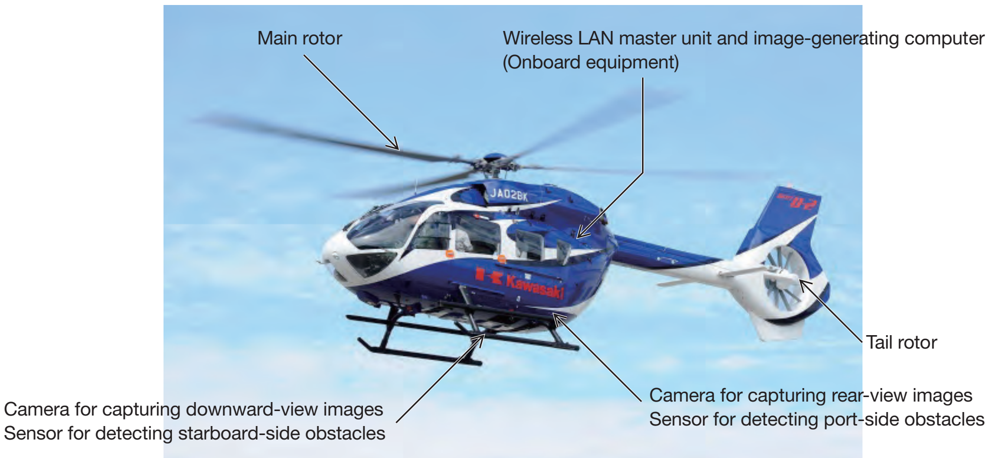


Fig. 2 Image of installation

Table 1 Specifications of laser radar from Velodyne

Sensor type	16 lasers and detectors
Detection range/angle	360° horizontally; all directions 30° vertically (+15° to −15°)
Detection distance 〔m〕	Approx. 100 (1 to 100)
Number of measurement points 〔points/s〕	Approx. 300,000 points/s
Measurement accuracy	± 3 cm (1 σ @25m)
Laser class	Class 1 Eye Safe
Laser wavelength 〔m〕	903
Weight 〔g〕	Approx. 830
Size 〔mm〕	H 71.7 × ϕ 103.3

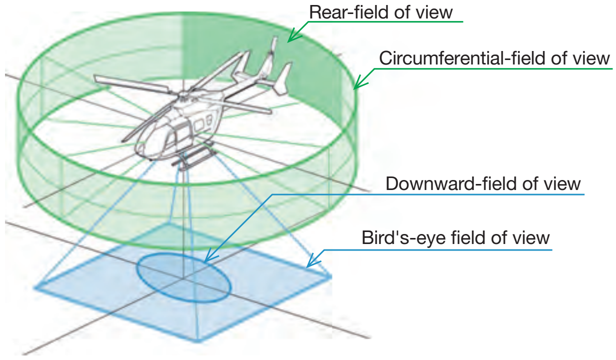


Fig. 3 Field of view of the external view camera

(3) Dedicated display unit

We used a general-purpose tablet-type display and a head mount display (HMD) as dedicated display units, in order to be independent of the helicopter's power supply. To minimize the cost of installing this system in an actual helicopter, this system employs a wireless LAN system for communication between the displays and the image-generating computer. These devices are not to be permanently installed in an aircraft; they are completely portable.

(4) Image-generating computer

The image-generating computer generates images for each crew member based on: (1) the inertia sensor signals representing the helicopter's attitude, location and speed, which are critical for understanding the situation during hovering; (2) the information from the obstruction detection sensors; and (3) the images from the external view cameras. This is a dedicated computer specialized for the environment of aircraft-installed devices.

A laptop PC with an equivalent capability was used for this system for demonstration and assessment.

4 Prior confirmation of the system for demonstration and assessment

The following describes the results of element tests carried out with the system for demonstration and assessment.

(1) Inspection information presented by the dedicated display unit

Referring to the opinions of helitack crews, we designed what information should be presented on the dedicated display unit.

Figure 4 shows examples of display screens. In the display for hovering situations, helicopter sits at the center, surrounded by a series of concentric rings that indicate the distance of obstacles from it. The system color-codes obstacles on the screen according to their distance from the helicopter: red is 5 to 15 m from the helicopter; yellow is 16 to 25 m; and green is 26 to 36 m. Obstacles beyond 36 m are not displayed. A blue line indicates the horizontal movement vector showing the helicopter's direction and speed. On the right is a vertical movement speed bar and altitude information. In addition, the vertical movement speed is displayed in the upper right, and the horizontal movement speed in the upper left, both numerically.

The lower half of the screen shows images from the rear-view and downward-view cameras. The rear-view images are reversed in the same way that drivers see an image in their rear-view mirror. When displaying downward-view images, the system superimposes a silhouette of the helicopter (CG) to assist with perspective. Touching the small image frame in the bottom-left corner switches between the rear view and the downward view.

The HMD only displays information during hovering situations.

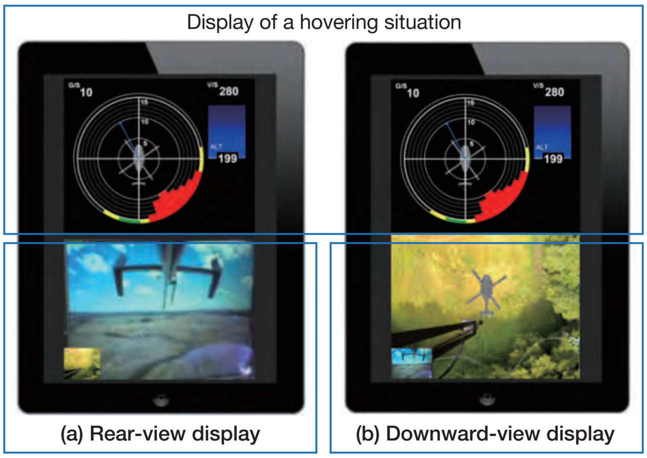


Fig. 4 Display example of the dedicated display unit

(2) Checking the performance of Velodyne's laser radar

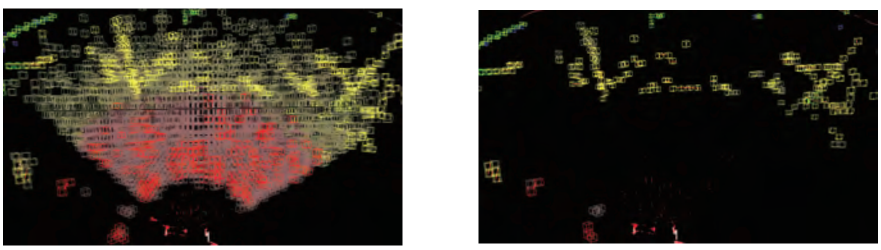
By checking the accuracy of distance measurements between the laser radar and a target, we confirmed that the error was 50 cm or less at ranges of 1 to 100 m.

To check how different materials affect system performance, we captured field data confirming detection of buildings and trees. **Figure 5** shows radar data and a photograph of the corresponding site.

The laser radar also detects snowflakes and large rain drops as obstacles. Although this system has been designed for visual flights, its data-processing capability can reduce interference from flying objects such as snowflakes, taking into account temporary bad weather that rescuers may encounter in a mountain area. This processing algorithm ignores observation data within point-blank range such as the space directly under the rotating main rotor. Also, the decision criteria for obstacles, i.e. the number of detection events in a certain time interval, are weighted according to distance from the sensor. At close ranges, the system classifies detection events as obstacles only when detections are made many times at the same position. For greater distances, the number of detection events, or the criteria, is smaller. Moreover, the criteria vary according to the speed of the helicopter; for example, they increase when the speed is lower than a certain value.

Figure 6 shows the obstacle-detection results when the criteria are varied according to distance when in a

Fig. 5 Comparison between data acquired by radar and photo



(a) Before data processing (b) After data processing

Fig. 6 Obstruction detection results in snow hovering state. Obstacles are detected without being affected by snow.

The validation of criteria in states of movement will be evaluated in the future.

(3) Flight test with a radio-controlled helicopter

To evaluate the impact of vibrations on the laser radar and cameras, we installed this system for demonstration and assessment on a radio-controlled helicopter, and conducted a flight test.

Figure 7 shows the experimental equipment. Web-cameras for rear and downward views were installed on the helicopter, and a laptop PC and an inertia sensor were set up inside a box attached beneath the helicopter body.

In real-life situations, the dedicated display unit would be inside the helicopter to monitor nearby obstacles and flight conditions. However, in this test these monitoring data from the radio-controlled helicopter were received on the ground.

The results show that the vibrations from the helicopter did not greatly affect the camera images or the laser radar detection.

Figure 8 shows some images captured in this test and displayed on the dedicated display unit's screen. The graphic in the upper left shows hovering situation data when the tail rotor gradually approached the hill, and the bottom-left image shows a rear view. The hovering situation data shows that obstacles are approaching the helicopter from the rear starboard direction. The large image is a picture of this helicopter captured from a remote location.

(4) Checking the effects of the wireless LAN system on an actual helicopter

This system uses wireless LAN as a way to transmit data from the image-generating computer to the dedicated display unit. Although this is effective for reducing weight and wiring work, it may affect the helicopter's electronics. For this reason, we conducted a demonstration and assessment test with part of the system under

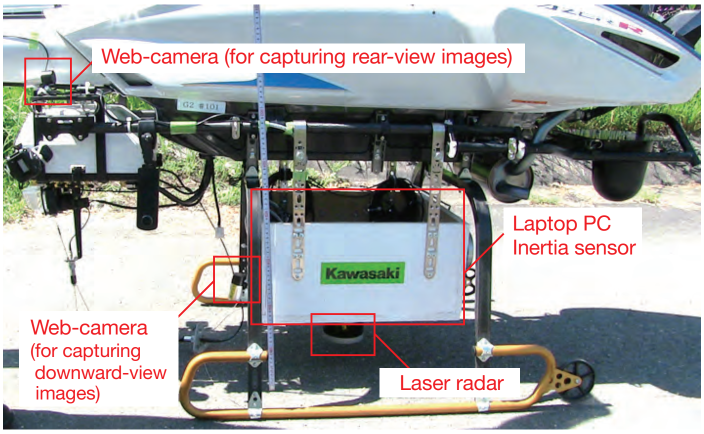


Fig. 7 Equipment of the system for demonstration and assessment

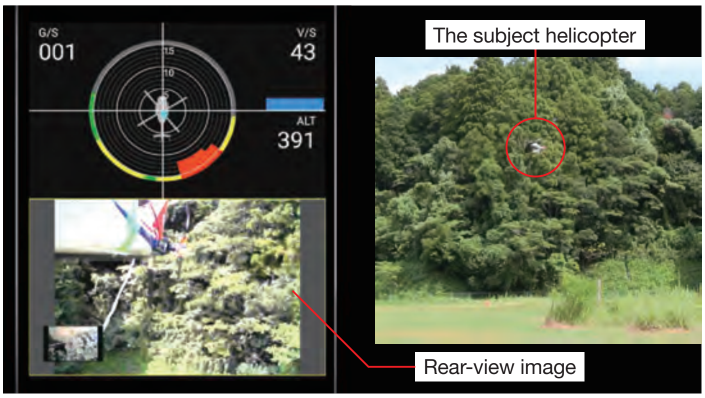


Fig. 8 Image of the dedicated display unit (left bottom) and flight movie (right)

development.

This test used 2.4-GHz band wireless LAN equipment, which was set up near the cockpit, which may contain several electronic devices. An external monitoring web-camera was installed on the right side of the back seat, and another camera was used to visually check whether the wireless LAN would be shut down.

The test results showed that the wireless LAN's radio waves did not adversely affect the helicopter's electronic systems such as the display device, the intercom system, the GPS device, or the external radio communication device. Furthermore, when the helicopter's electronic systems were operated while the dedicated display unit was constantly running, its display and image switching operations worked normally.

Conclusion

To build a prototype of this system for installation in an actual helicopter, we are now selecting small and inexpensive obstruction detection sensors and image-acquisition cameras that can be installed in a helicopter. We plan to install this prototype in a BK117 helicopter to conduct a flight test in the latter half of fiscal 2019. While issues including cost and size remain to be solved, we are now developing this system with the aim of commercializing it.

To develop this system, we received valuable opinions from personnel of the Gifu Disaster Prevention Air Corps, the Saitama Disaster Prevention Air Squadron, the Ehime Disaster Prevention Air Corps, the Tokushima Fire Fighting Disaster Prevention Air Corps, and the Kagawa Disaster Prevention Air Corps. They provided invaluable feedback and advice perspectives from operators' points of view. We would like to express deep gratitude to all of them.

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Airborne Telemetry Network Technology

The flight test is conducted for final performance verification during aircraft development. At the flight test, data is transmitted to the ground with telemetry technology to monitor safety and determine whether the test is successful. We work on applying the technology of the telemetry network equipped with high-capacity communication and bidirectional communication functions to the flight test in order to address an increase in measurement data in line with advancements made in onboard airborne systems and communication from the ground to the aircraft. We are now demonstrating this technology using helicopters and will apply it to fixed-wing aircraft in the future.

Introduction

In the development and improvement of aircraft, flight tests are conducted to verify the final performance, functionality and safety. During a flight test, data is transmitted from the aircraft to the ground with telemetry technology to monitor safety and determine whether the test is successful.

1 Background

During flight test, it is critical to acquire information such as stress and vibration data to evaluate the aircraft's structure, inter-equipment communication data to evaluate the onboard systems, and image data to capture the operating status of the equipment. And since aircraft structure, onboard systems and equipment are becoming increasingly sophisticated every year, the amount of data required is increasing.

However, only selected data is actually transmitted out of the data acquired because of restrictions to the volume of data that can be transmitted with telemetry technology 1). Moreover, as the amount of data required continues to grow, it is predicted that it will be difficult for conventional telemetry technology to handle flight tests.

In addition, from the viewpoint of improving flight-test efficiency, various other requirements are expected to place an increasing burden on telemetry systems such as data transmission from the ground to the aircraft, controlling onboard measurement equipment, and retransmission data that could not be transmitted due to the radio interference. These all require bidirectional communication, which also is not supported by conventional telemetry technology.

To solve these problems, we have launched research into telemetry network technology to realize a faster communication rate as well as bidirectional communication.

2 Overview of telemetry network technology

Telemetry network technology acquires data with ethernet-based measurement equipment, and as shown in **Fig. 1** illustrates how each piece of equipment is connected via network switches. This technology consists of three networks: an onboard network installed on the aircraft, a bidirectional RF radio communication network, and a ground network. The RF network provides communication between the onboard network and ground network via network transceivers.

The telemetry network led by the US Department of Defense (DoD) is called iNET (integrated Network Enhanced Telemetry), which was added in 2017 to IRIG 106, a telemetry technology standard.

iNET will be the standard going forward in-flight tests conducted by the DoD. The DoD has a large number of flight-test areas and plans to apply this iNET technology to conduct flight tests over a wide range covering each area.

Figure 2 shows an overview of iNET, where bidirectional communication takes place between airborne aircraft; on the other hand, communication between aircraft and the ground is performed in combination of bidirectional and unidirectional communication.

Our telemetry network technology conforms to this standard.

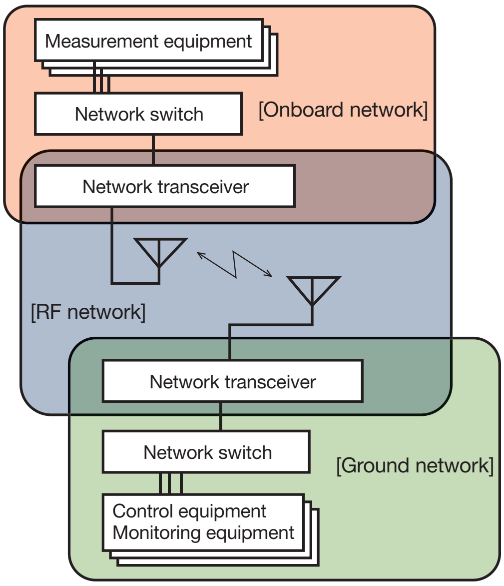

Fig. 1 Overview of the telemetry network technology

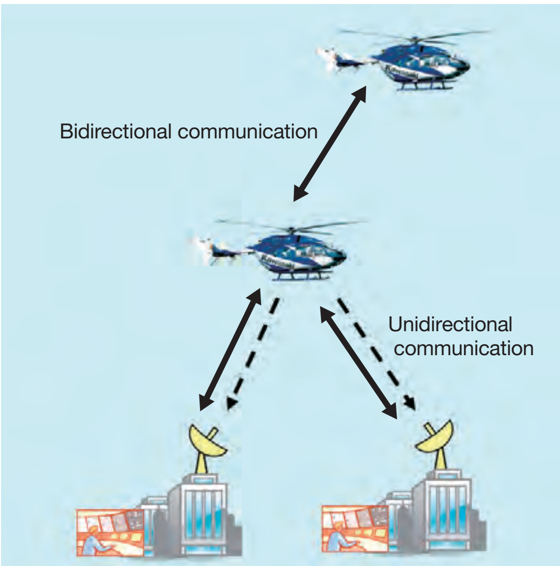

Fig. 2 Overview of iNET

3 Comparison with conventional technology

In conventional telemetry technology, data is transmitted unidirectionally from the aircraft to the ground. The data acquired onboard is converted to serial data (PCM data) and frequency or phase-modulated, then finally transmitted. The communication speed achieved in our company is up to around 3 Mbps in S-band telemetry[1].

On the other hand, telemetry network technology enables bidirectional communication. It packetizes data acquired onboard according to the ethernet standard and transmits the packets via network transceivers using OFDM (Orthogonal Frequency Division Multiplexing), compliant with the wireless LAN standard IEEE802.11a. Furthermore, it automatically switches the modulation method to 16QAM, QPSK, or BPSK depending on the radio signal reception strength. The estimated maximum communication speeds are about 20 Mbps, 10 Mbps, and 5 Mbps, respectively - much faster than the conventional system. Moreover, its bidirectional communication functions allow onboard equipment to be remotely controlled and interrupted data to be retransmitted - functions that the conventional technology does not support. The new technology also makes it possible to connect ethernet-based equipment such as a network camera, or add various other functions by developing software for them.

Figure 3 shows the appearance of the network transceiver we are using, and **Table 1** lists its specifications.

Fig. 3 Appearance of network transceiver

Table 1 Specifications of network transceiver

Center frequency (MHz)	2,200 ~ 2,400
Occupied band (MHz)	20 or less
Transmission output power (W)	80 (peak)
Modulation system	OFDM (802.11a)
Interface	Ethernet
Dimensions (mm)	W 159 × D 168 × H 74
Weight (g)	2,903

4 Telemetry network technology applied in this company

Among the three networks mentioned above, we have already demonstrated the onboard network, and are now preparing to demonstrate the RF network. Specifically, we are working on applying the RF network to flight tests to demonstrate the communication range, communication rates and bidirectional communication functions. We are also accumulating knowledge on various settings to demonstrate these functions and how equipment should be installed in aircraft.

(1) Securing efficient and stable communication rates

As radio signal strength constantly fluctuates during a flight test, securing an efficient and stable communication rate is essential. Since the communication rate varies depending on the modulation method, we are testing settings such as for the procedure to switch between modulation systems and on the reception-level threshold for the switching under various reception conditions during flight tests.

(2) Optimizing time allocation for communication

This telemetry network technology uses TDMA (Time Division Multiple Access) to allocate time for communication, and the downlink from the aircraft to the ground and the uplink from the ground to the aircraft are allocated different periods of time. Since the way time should be allocated between the ground and the aircraft is also important, we are trying various ratios during flight tests to find the optimal allocation.

(3) Checking data retransmission functions from aircraft

We are also working on adding a new function that utilizes the characteristics of bidirectional communication. When communicating by telemetry technology, there may be some instances where obstacles between the aircraft and ground facility or the aircraft's attitude variations may disrupt communication between antennas. In such a case, retesting is required due to the deficiency in the received data caused by radio disruption. To address this problem, we have developed a function that sends a data retransmission command from the ground to the aircraft for the data to be transmitted again, by taking advantage of the bidirectional communication features of the telemetry network technology. This function is also being demonstrated under various conditions of radio disruption in flight tests.

Table 2 presents a list of tests conducted so far regarding the above. In a communication test conducted in 2015, we demonstrated telecommunication using a moored airship at the Taiki Aerospace Research Field in Hokkaido. We established communication speeds up to approx. 20 Mbps with the airship at an altitude of 120 m and a distance of 34 km.

5 Demonstration by a flight test using a helicopter

In FY2016, we started in-flight demonstrations using a helicopter. These tests are to confirm whether the communication range, communication rates, and the overall functions are applicable to aircraft flight tests. The following describes the FY2016 demonstrations.

(1) Equipment and facilities

Flight test vehicle: Kawasaki BK117 C-2 helicopter.

(i) Equipment installed in the aircraft

Since the measurement equipment was to be used temporarily for the study, it was installed in a simplified way as shown in **Fig. 4** to minimize modifications. Major pieces of equipment were fixed in the cabin, a telemetry antenna to an existing stay, and a GPS antenna to an entrance handgrip.

The GPS antenna is equipment needed to synchronize communication between the aircraft and the ground.

(ii) Facilities on the ground

Figure 5 shows the ground facilities, comprising an antenna placed on a roof of our Gifu Works building, a

Table 2 Details of test conducted

Year	Contents
2007	Investigation into telemetry network technology
2014	Introduction of telemetry facilities for flight tests
2015	Bidirectional telemetry communication test using a moored airship
2016 2017	Demonstration of bidirectional telemetry using a helicopter

Fig. 4 Equipment in fuselage

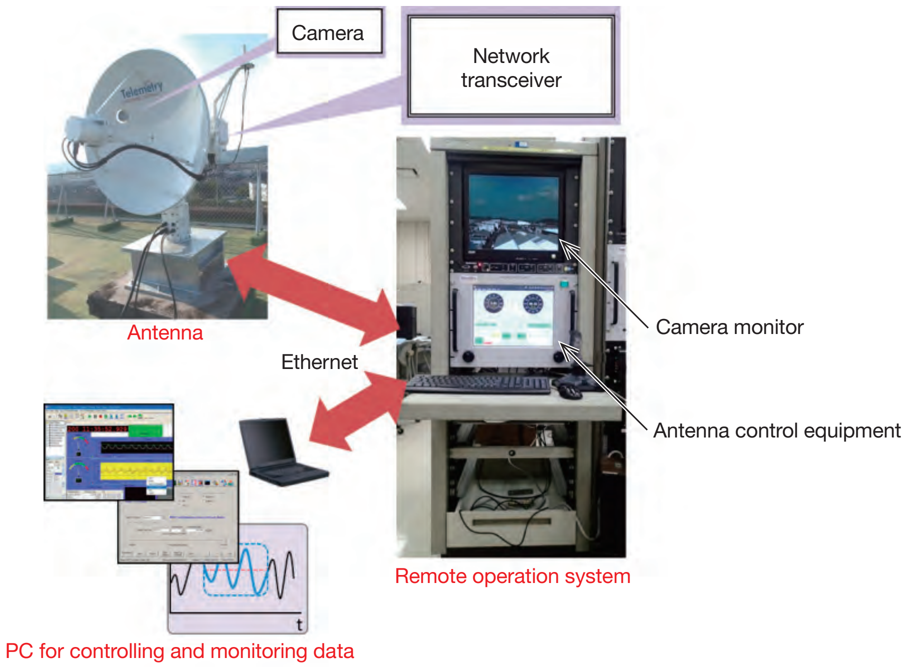

Fig. 5 Ground facilities

remote-operation system, and a PC for controlling and monitoring data installed in the monitoring room.

The antenna can automatically track the aircraft by obtaining the location information from the network transceiver installed in the aircraft. With the PC for controlling and monitoring, we measured communication parameters such as communication rates.

(2) Overview and results of the flight test

We tested the following items while flying the aircraft between our Gifu Works and a place within 50 km of the Works as shown in **Fig. 6** : checking the communication range and rates, controlling onboard measurement equipment from the ground, and retransmitting data following radio signal interruptions.

In conclusion, we achieved a communication rate of 5 Mbps at a communication range of 50 km, and confirmed onboard measurement equipment could be controlled from the ground, and data could be retransmitted when the radio signal had been interrupted.

Regarding the communication rate, we now see the prospect of establishing 10 Mbps in subsequent analysis.

Testing is still underway with different settings of the onboard measurement equipment, and we are obtaining better results in terms of communication range and speeds.

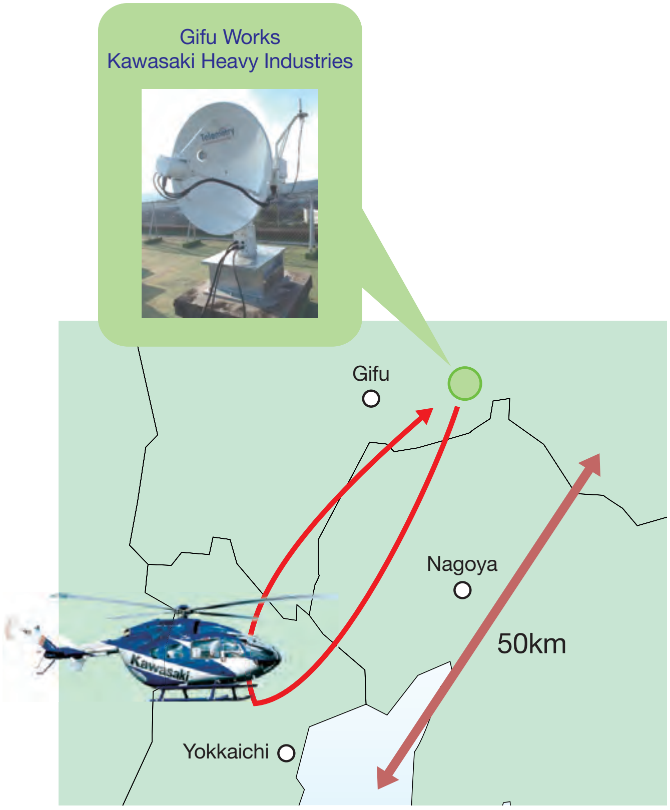

Fig. 6 Overview of test

Conclusion

Telemetry network technology is a system that has not been used in Japan to date, but will become a standard for flight tests going forward, so we will continue our research to put into practical use. Our goals are to further extend the maximum communication range and demonstrate the technology using faster aircraft, such as a fixed-wing one.

Furthermore, we will work on applying this technology to systems for transmitting data, such as image data, to assist information sharing among search-and-rescue aircraft dispatched in a disaster.

Reference

1) Ito: "Flight Test Real-Time Monitoring System," Kawasaki Heavy Industries Technical Review No. 171 pp.52-53 (2011)

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Maritime Patrol Aircraft P-1 and Cargo Aircraft C-2

Source: Ministry of Defense (MOD)

The fixed-wing maritime patrol aircraft P-1 has been developed as a successor of the P-3C, which is currently used by the Maritime Self-Defense Force, to conduct many different missions including wide scale warnings, surveillance and patrol in the surrounding sea areas of Japan.

The cargo aircraft C-2 is the largest aircraft made in Japan developed as the successor to the C-1 and other aircraft in the Air Self-Defense Force. The C-2 is mainly intended to quickly deploy operating forces in emergency situations and conduct air transportation necessary for completing activities of the Self-Defense Force in time of peace.

We have significantly reduced development costs by jointly developing them at the same time.

Introduction

There are growing needs for wide-scale early warning and surveillance in the seas surrounding Japan and for the Self-Defense Force to perform air transportation activities.

1 Background

In 2001, we were designated as the lead company to develop the P-1 maritime patrol aircraft and C-2 cargo aircraft, and started designing and manufacturing various prototypes. Following delivery of the first mass-produced P-1 in 2013, mass production continued steadily before we receiving a bulk order for 20 aircraft in 2016. Since conducting the first prototype C-2's maiden flight in 2010, we have enhanced the design through a rigorous series of tests to complete development at the end of FY2016. We are now mass-producing C-2 aircraft.

2 Product overview

(1) P-1

The size and weight of the P-1 airframe are about the same as those of the current P-3C (**Table 1**).

The P-1 employs the world's first practical fly-by-light flight control system, which offers outstanding resistance to electronic magnetic interference. Moreover, the newly developed sonobuoy and radar systems feature improved capabilities for detecting submarines and suspicious ships. Powered by the new, domestically developed high-bypass-ratio turbofan engines (IHI's F7-10), the P-1 outstrips the current P-3C both in mission capability and airframe performance.

In addition to the radar, the P-1 also carries various sensors such as infrared, sonobuoy, and magnetic anomaly detection systems to search for and locate potential seaborne threats. And a bomb bay beneath the fuselage

Table 1 Comparison between maritime patrol aircraft P-1 and P-3C

Item	P-1	P-3C
Engines	F7-10 (Turbofan)	T56 (Turboprop)
Length〔m〕	38.0	35.6
Wingspan〔m〕	35.4	30.4
Overall height〔m〕	12.1	10.3
Basic take-off weight〔t〕	79.7	56.0

and missile pylons under the wings transform the aircraft into a formidable attack platform. Defending the P-1 against missiles is its flare deployment system (**Fig. 1**).

(2) C-2

The C-2's maximum take-off weight is about three times heavier than that of the current C-1 (**Table 2**).

The C-2, with the largest airframe ever developed in Japan, outperforms the current, similar-looking C-1 in terms of speed, loading capacity, and cruising range. It is also capable of aerial refueling to extend its range and time aloft. Moreover, the brand-new flight management system and labor-saving load management system reduce operator workloads. Powering the C-2 is a pair of General Electric


Source: Ministry of Defense (MOD)

Fig. 1 Avoiding missiles by deploying flares

Table 2 Comparison between cargo aircraft C-2 and C-1

Item	C-2	C-1
Engines	CF6-80C2	JT8D
Length〔m〕	43.9	29.0
Wingspan〔m〕	44.4	30.6
Overall height〔m〕	14.2	9.99
Maximum take-off weight〔t〕	141	45

CF-6 high-bypass-ratio turbofans. Possessing a reputation for reliability, these are the same engines employed on the Air Self-Defense Force's KC-767s and E-767s.

The cargo compartment is 15.7 m long and 4 m high with a large back door that opens vertically. This door doubles as a loading ramp that allows vehicles such as trucks to drive straight into the cargo bay for transportation by air (**Fig. 2**). This door can also open during tactical missions for aerial delivery of cargo and paratroopers (**Fig. 3**).

(3) Simultaneous development of common-use components

We employed a design principle in which the C-2 and P-1 share the following components: structural parts such as cockpit windshields, outer half of wings, and horizontal tails; and equipment such as display units, inertial reference units, flight control computers, auxiliary power units (APUs), anti-collision lights, and landing gear retraction system control units. Shared components


Source: Ministry of Defense (MOD)

Fig. 2 Driving a truck into the aircraft


Source: Ministry of Defense (MOD)

Fig. 3 Air drop

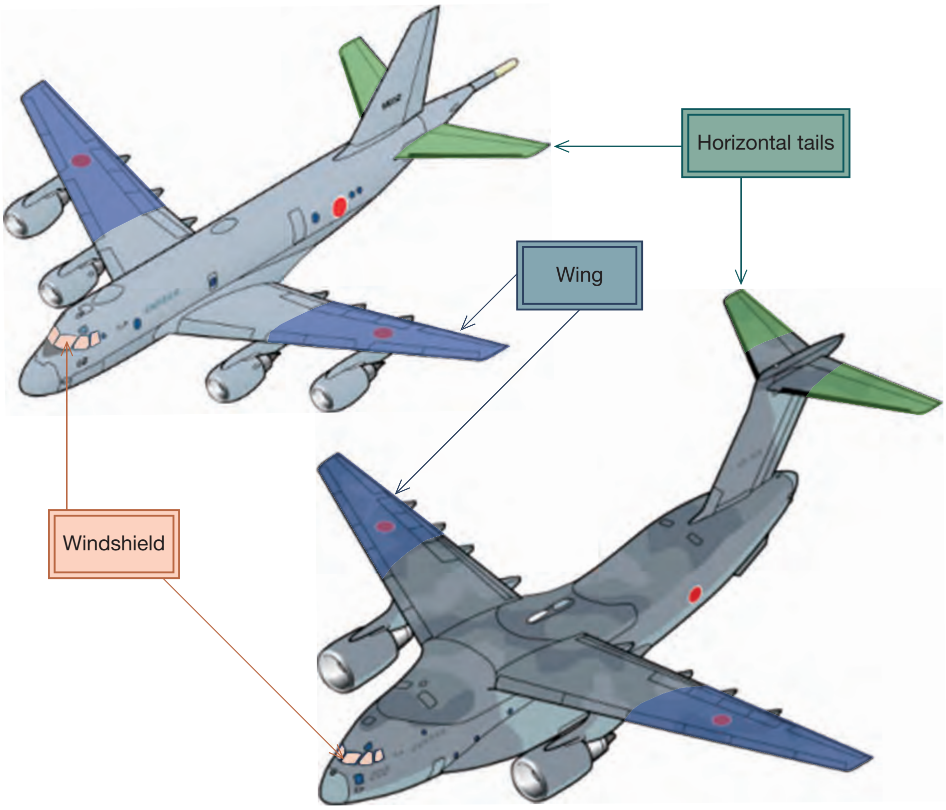

Fig. 4 Shared structural parts of fuselage (left: P-1, right: C-2)

account for about 25% of the aircraft's weight, and about 75% of the total number of installed systems are common pieces of equipment (**Fig. 4**).

Conclusion

The new P-1 and C-2 have been simultaneously developed through the combined efforts of the Ministry of Defense and Japanese aircraft manufacturers. The P-1's development concluded in FY2013, and the C-2's finished in FY2016. Currently, the Self-Defense Force is operating the first to fifteenth P-1 planes and the first to seventh C-2s for national defense. We will continue to deliver these mass-produced aircraft and support the troops' operation of them, as well as propose export of these aircraft and develop derivative models.

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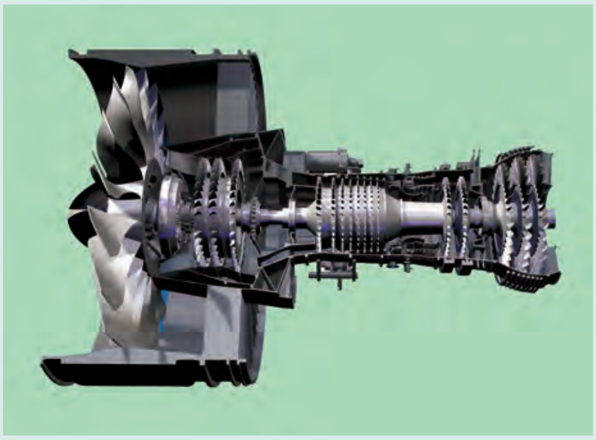
Regional Jet Engines PW1500G and PW1900G



As the global demand for aircraft has been increasing year by year, environmentally friendly engines have garnered attention. The regional jet engines PW1500G and PW1900G are geared turbo fan engines that employ an advanced gear system to attain a high bypass ratio, improve fuel efficiency by 16% and reduce noise by 50% compared with conventional aircraft, and significantly reduce CO_2 and NOx emissions as well. We are in charge of the core parts of these jet engines, that is, the combustor and the fan drive gear system.

Introduction

The demand for aircraft increases year by year in line with global population growth and the economic development in emerging countries in Asia, South America and other regions. This trend is expected to continue in the future. In this growing market, every airline wants fuel-efficient aircraft and so environmentally friendly engines are gathering attention.

Although we contribute to this program mainly with our manufacturing technologies, we believe that we can realize low costs and stable quality by refining element, design and manufacturing technologies such as those we use in this program in a comprehensive way. Therefore, we are developing element technologies to sophisticate aeroengines and upgrading aviation gearbox design technologies as well.

1 Background

Kawasaki is participating in Pratt & Whitney's (PW) development and production program for their next line of regional jet engines, Pure Power PW1500G and PW1900G, with the RRSP method. Under this contract, contractors receive allocations of all business income from the sales, repair and other businesses of engines and spare parts in proportion to their participation, but also proportionately incur all the expenditures and risks related to development, mass-production and sales. In this program, KHI has produced combustors and is in pre-production for the manufacture of a fan drive gear system. These are some of the essential parts of the engine and they play an important role in improving engine performance.

In addition, we are developing technologies with an aim to be a supplier of three modules, that is, compressor, combustor and gear. In this program, we are in charge of two of these three modules that we are focusing on.

2 Specifications

The main specifications of the PW1500G and PW1900G are shown in **Table 1**. These models realize a high bypass ratio by adopting an advanced gear system. They are geared turbo fan engines that improve fuel efficiency by 16% and reduce noise by 50% from the previous model and significantly reduce CO_2 and NOx. We are in charge of their core sections, that is, the combustor and the fan drive gear system (**Fig. 1**).

3 Features

(1) Combustor

The combustor is the part that generates hot combustion gas to drive the engine by mixing air taken into the engine with aviation fuel and combusting the mixture (**Fig. 2**). Therefore, this part becomes the hottest in the engine with the temperature of the combustion gas

Table 1 Main specifications

	PW1500G	PW1900G
Thrust〔lb〕	19,000 ~ 23,300	~ 23,000
Bypass ratio	12 : 1	12 : 1
Fan diameter〔in〕	73	73

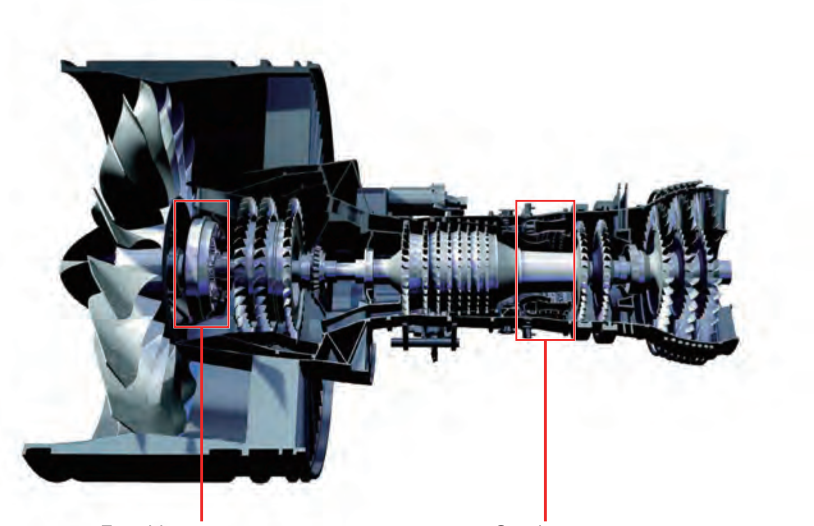


Fig. 1 Positions of combustor and fan drive gear system

exceeding 2,000°C. It is required to efficiently combust fuel in this environment, while reducing the emissions of hazardous NOx at the same time.

We make the most of our experience in designing and manufacturing combustors for military aircraft engines and in mass-producing combustors for industrial engines. For example, we have designed and manufactured the combustor for turbo fan engines with a high bypass ratio used in a fixed-wing patrol aircraft, the P-1.

(i) Temperature rise

The combustor has numerous small cooling holes to keep cool while managing hot combustion gas. We leverage a state-of-the art laser processor and discharge processor to precisely place these holes in the specified positions.

Removable molded heat-resistant panels with a highly heat-resistant coating are adopted as the inner wall that comes in contact with the combustion gas to ensure a long lifetime. In addition, these panels can be replaced as needed during maintenance.

(ii) Reduction in NOx

The combustor consists of various components including the fuel nozzle, which emits fuel to provide an even mix of the fuel into the air for the combustion mixture, along with the air holes supplying the air mixture. Our experience is put to use again to apply advanced sheet metal forming technology and welding technology to accurately reproduce their shapes and dimensions as

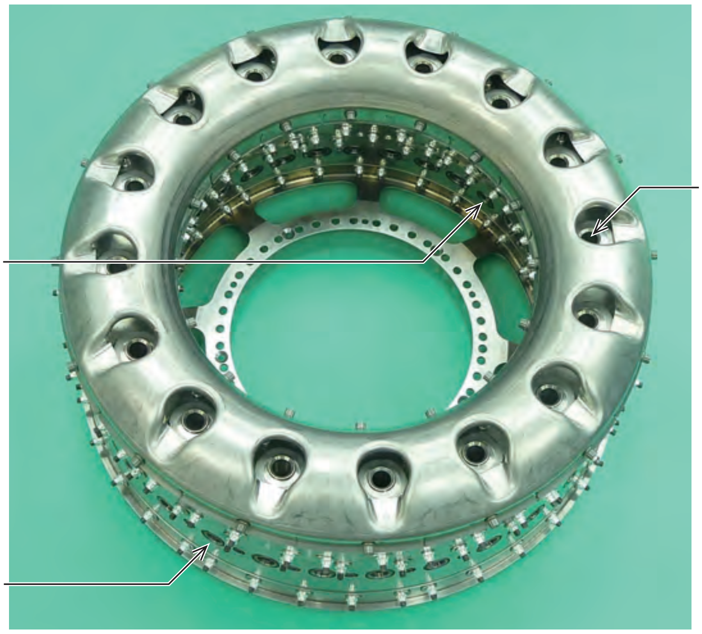


Fig. 2 Combustor

designed through repeated advanced analysis and experiments.

(2) Fan drive gear system

In a conventional two-shaft engine, the low-pressure shaft and the fan are directly connected and rotate at the same speed. Since the fan with a large diameter becomes less efficient as the tip speed approaches the speed of sound, a lower rotation speed is desirable. In contrast, it is desirable to increase the rotation speed of the low-pressure compressor and low-pressure turbine with its smaller diameter to increase the load per stage and reduce the number of stages. The geared turbo fan engine decelerates the rotation from the low-pressure system in the gearbox and rotates the fan to set desirable rotation speeds to both of them.

The fan drive gear system uses star-shaped epicyclic gearing because the input and output are on the same shaft and the horsepower delivered per capacity unit is large (**Fig. 3**).

We develop, manufacture, repair and overhaul transmissions for helicopters including the BK117, accessory boxes for aeroengines, a constant frequency generator for aircraft that applies the traction drive CVT (continuously variable transmission), the T-IDG, and other products. We have also used the experience we gained in developing the technologies for open rotor power gearboxes.

4 Product delivery

Kawasaki shipped the first PW1500G combustor for the engine in the newest regional jet airplane, the C Series of Bombardier in Canada from Akashi Works to PW on May 29, 2017. This is the first combustor that we manufactured for commercial aircraft engines.

We plan to ship specimens for rig and engine tests on the fan drive gear system to PW and start production in 2019.

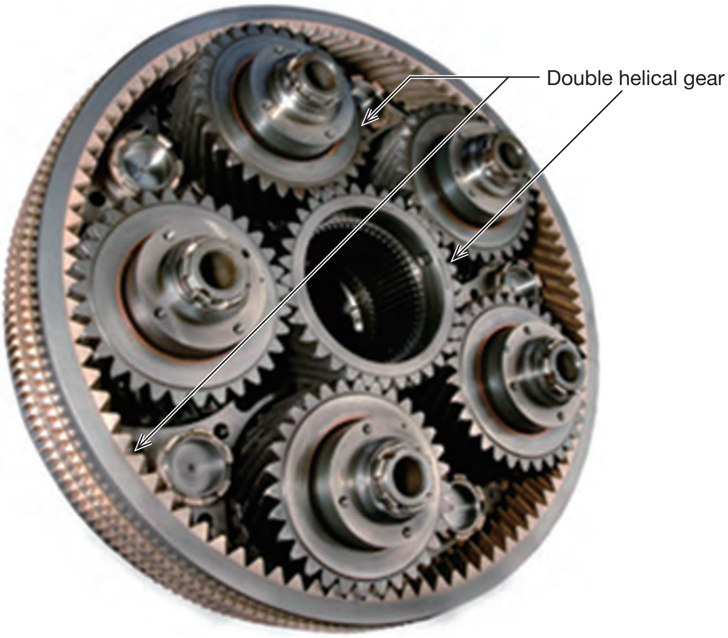


Fig. 3 Fan drive gear system

Conclusion

The PW1500G is used exclusively in the C Series. The PW1900G is a derivative engine of the PW1500G and it is used exclusively in the E190E2 and E195E2, the newest regional jet airplanes from Embraer in Brazil.

It has been published that orders for more than 600 C Series, E190E2 and E195E2 have been confirmed in total. More than 1,200 engines will be mounted on their fuselages. We will improve our technologies so that our products will remain popular.

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High-Performance, Twin-Engine, Multi-Purpose Helicopter H145//BK117 D-2

As the demand for civil helicopters is increasing in a wide range of areas, we are working on improving adaptability to performance requirements in these various applications.

The H145//BK117 D-2 is the latest model of the Twin-Engine, Multi-Purpose Helicopter series that Kawasaki and German-based MBB (now Airbus Helicopters Deutschland GmbH) have continued to jointly develop.

We have realized significantly improved performance by the adoption of new engines with improved transmission, reduced pilot workload with the four-axis autopilot in conjunction with new integrated instruments, and enhanced safety with reduced noise by adopting the Fenestron tail rotor.

Introduction

As the safety and reliability of helicopters have improved, demand for civil use of them keeps growing in a wide range of applications such as firefighting and disaster prevention, emergency medical services, police, broadcasting, and transport for people.

In this light, Kawasaki and Germany-based MBB (now Airbus Helicopters Deutschland GmbH) have continued to jointly develop the Twin-Engine Multi-Purpose Helicopter BK117 since 1977. Over 1,300 units of this model have been delivered around the world.

1 Background

In general, helicopter performance declines in the thinner air of high temperatures or high altitudes, and higher engine output is required to maintain the flight condition of zero forward speed, such as hovering and vertical climb. So, when assuming a high-load flight under any combination of these conditions, it is critical to reduce the helicopter's total weight (gross weight) before flying by restricting the equipment, crew, and fuel it will carry.

Medium-sized, twin-engine, multi-purpose helicopters like the BK117, are generally assumed to operate under high-load flight conditions, such as hovering at high altitudes in mountain rescues and vertical take-offs/landings in confined areas. In addition to adaptability to these flight conditions, the market has called for universal improvements to aircraft performance such as higher maneuverability, lower noise, and better safety.

We have further improved BK117 by boosting performance, reducing the pilot's workload, lowering noise, and enhancing safety. These upgrades have culminated in obtaining certification for the H145//BK117 D-2 (model D-2) in Japan in January 2016.

2 Specifications

Table 1 shows the specifications of the latest model D-2 and the conventional Kawasaki BK117 C-2 (model C-2). **Figure 1** shows an appearance of model C-2. The D-2 comes equipped with improved engines and a higher transmission power rating. Regarding the limitation of engine rated power output when one engine is inoperative (OEI), the D-2 applies significantly higher output on demand for 30-second/2-minute OEI power to the operating engine compared to the C-2 (2.5 minutes).

3 Features

The D-2 offers higher performance, reduced pilot workload, lower noise, and lower maintenance costs.

† Realized the world lowest level of noise in its class, better hovering performance and longer lifetime through adoption of a new tail rotor and other components.

Table 1 Specifications of the latest D-2 and the conventional C-2

		D-2	C-2
Length × fuselage width × overall height 〔m〕		13.64 × 1.73 × 3.95	13.03 × 1.73 × 3.96
Seating capacity (standard seat) 〔persons〕		10	10
Maximum gross weight 〔kg〕		3,700	3,585
Maximum speed 〔km/h (kt)〕		265 (143)	269 (145)
Transmission power rating 〔kW (SHP)〕	30 sec power/OEI	662 (887)	-
	2 min power/OEI	574 (769)	-
	2.5 min power/OEI	-	548 (735)
	Continuous power/OEI	441 (591)	404 (542)
	Take-off power/AEO <available time>	838 (1,123) <30 min>	776 (1,040) <5 min>
	Continuous power/AEO	653 (875)	633 (848)
Engine power rating 〔kW (SHP)〕	30 sec power/OEI	800 (1,072)	-
	2 min power/OEI	775 (1,038)	-
	2.5 min power/OEI	-	528 (708)
	Continuous power/OEI	710 (952)	528 (708)
	Take-off power/AEO	667 (894)	528 (708)
	Continuous power/AEO	575 (771)	516 (692)

OEI : one engine inoperative,   AEO : all engines operative

Fig. 1 Appearance of model C-2

(1) Better performance

(i) Hovering performance

Although the D-2's maximum gross weight is higher than that of the C-2 by 115 kg, the D-2's out-of-ground-effect hover ceiling at the maximum gross weight is 2,316 m (7,600 ft) under atmospheric conditions where the surface temperature is 35°C (the International Standard Atmosphere Temperature + 20°C). This compares favorably to 2,103 m (6,900 ft) for the C-2.

(ii) Time available for using take-off power

The take-off power refers to the high power output used mainly for taking off, but it is frequently used while hovering and hoisting during rescue operations.

While the C-2's time available for using take-off power is five minutes, improving the transmission in the D-2 has stretched this out to 30 minutes. This improvement is a clear benefit in rescue operations involving difficult extractions and where several people are waiting for help.

(iii) Transport category A operation

The BK117 meets the requirements of Transport category A among the categories specified by the Civil Aeronautics Act. In compliance with the Act, this model is specified to use a safe take-off/landing method that assumes OEI at a location such as a rooftop helipad when other nearby emergency landing spaces are unavailable.

With its improved power rating under OEI, the D-2 can take off and land using this method with a higher gross weight than the C-2's. For example, at an altitude of 1,829 m (6,000 ft) and with a surface temperature of 35°C (the International Standard Atmosphere Temperature + 20°C), the D-2's allowable gross weight is 3,270 kg, which is 560 kg higher than the C-2's.

(2) Reduced pilot workload

The D-2 employs the four-axis autopilot, adding an extra dimension to the C-2's three-axis aircraft attitude control (pitch/roll/yaw). This extra axis is the additional collective pitch control that can alter the thrust. This increased the number of mode selections from the conventional 10 to 15, opening up new range of conditions where pilots can engage the autopilot.

The D-2 also features a new integrated instrument, Helionix (**Fig. 2**). While the C-2 uses seven separate displays to show instrument data, the D-2 reduces this to

Fig. 2 Helionix in the D-2

Fig. 3 Fenestron

three large multifunction displays (MFDs). Pressing bezel keys on the periphery of an MFD enables pilots to quickly select which data to display on the screen. This reduces the workload by providing pilots with operator-friendly visual information according to the situation.

(3) Quieter than ever before

Instead of the two-blade tail rotor installed on the C-2, the D-2 employs a Fenestron (**Fig. 3**). The shroud around the Fenestron's rotor cuts noise. Moreover, rotor blades that are intentionally arranged with uneven spacing, and ten stators with different angles, also reduce noise around the aircraft.

(4) Improved safety

Due to a higher power rating with its new engines, the D-2 has excess power for avoiding collision and improved altitude-maintaining capability at the time of one engine inoperative (OEI). In addition, it uses computerized engine control to offer a training function that simulates the behavior during OEI with all engines operative (AEO). Thanks to this function, the pilot can safely go through the emergency operation training in case of OEI.

Moreover, the four-axis autopilot and Helionix reduce pilot workload to enhance safety, and the adoption of the Fenestron tail rotor reduces the risk of the tail rotor getting in contact with an obstacle when operating in confined areas.

(5) Lower maintenance costs

The D-2 offers lower maintenance costs achieved through extended maintenance intervals arising from improved engine durability.

Conclusion

We are now promoting sales of the D-2, targeting firefighting, disaster prevention and emergency medical services. Various items of optional equipment for these applications are now under development to enhance this aircraft's value to its users.

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Kawasaki Heavy Industries Group

Main Products and Production Bases by Business Segment

Business Segment	Main Products	Main Production Bases
Ship & Offshore Structure	• LNG carriers, LPG carriers, crude oil carriers, bulk carriers, container ships, car carriers, high-speed vessels, submarines, ships for government and municipal offices	Kobe Works (Kobe, Hyogo Prefecture) Sakaide Works (Sakaide, Kagawa Prefecture) Nantong COSCO KHI Ship Engineering Co., Ltd. (China)* Dalian COSCO KHI Ship Engineering Co., Ltd. (China)*
Rolling Stock	• Train cars, integrated transit systems, freight cars • GigacellTM (nickel metal-hydride battery)	Hyogo Works (Kobe, Hyogo Prefecture) Harima Works (Harima-cho, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Rail Car, Inc. (U.S.A.)
	• Rotary snowplows, de-icing vehicles • Rail cars, heavy lift cars	NICHIJO CORPORATION. Head Office (Main Plant)(Sapporo, Hokkaido) Akebono Plant (Sapporo, Hokkaido)
Aerospace Systems	• Aircraft (fixed-wing aircraft and helicopters), missiles, electronic equipment, space systems and peripheral equipment, simulators	Gifu Works (Kakamigahara, Gifu Prefecture) Nagoya Works 1 (Yatomi, Aichi Prefecture) Nagoya Works 2 (Tobishima-mura, Aichi Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.)
	• Aircraft components, target systems, rocket components, space equipment, remodeling	NIPPI Corporation Aerospace Division (Yokohama, Kanagawa Prefecture) and Aircraft Maintenance Division (Yamato, Kanagawa Prefecture)
	• Aircraft engines	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe, Hyogo Prefecture)
Energy System & Plant engineering	• Gas turbine engines for ships • Gas turbine generators, gas turbine cogeneration systems	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe, Hyogo Prefecture)
	• Steam turbines, diesel engines, gas engines, large decelerators • Marine propulsion systems (side thrusters, steerable thrusters) • Natural gas compression modules, air blowers and other aerodynamic machinery	Kobe Works (Kobe, Hyogo Prefecture) Harima Works (Harima-cho, Hyogo Prefecture) Wuhan Kawasaki Marine Machinery Co., Ltd. (China)
	• Air conditioning equipment, general-purpose boilers	Kawasaki Thermal Engineering Co., Ltd. Shiga Works (Kusatsu, Shiga Prefecture)
	• Cement, chemical, conveyers, and other industrial plant systems • Industrial boilers for land and marine use • Waste treatment facility • LNG tank and other storage facilities • Shield machines, tunnel boring machines	Harima Works (Harima-cho, Hyogo Prefecture) Shanghai COSCO Kawasaki Heavy Industries Steel Structure Co., Ltd. (China)* Anhui Conch Kawasaki Equipment Manufacturing Co., Ltd. (China)* Anhui Conch Kawasaki Energy Conservation Equipment Manufacturing Co., Ltd. (China)* Shanghai Conch Kawasaki Engineering Co., Ltd.*
	• Crushers, environment-related equipment	EarthTechnica Co., Ltd. Yachiyo Works (Yachiyo, Chiba Prefecture)
Motorcycle & Engine	• Motorcycles, ATVs (all-terrain vehicles), recreational utility vehicles, utility vehicles, Jet Ski watercraft • General-purpose gasoline engines	Akashi Works (Akashi, Hyogo Prefecture) Kakogawa Works (Kakogawa, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Motores do Brasil Ltda. (Brazil) India Kawasaki Motors Put. Ltd. (India) Kawasaki Motors Enterprise (Thailand) Co., Ltd. (Thailand) PT. Kawasaki Motor Indonesia (Indonesia) Kawasaki Motors (Phils.) Corporation (Philippines) Changzhou Kawasaki and Kwang Yang Engine Co., Ltd. (China)*
Precision Machinery & Robot	• Hydraulic equipment for construction machines, hydraulic equipment and systems for industrial machines • Marine application machines, deck cranes and other marine deck equipment • Industrial robots • Medical and pharmaceutical robot	Akashi Works (Akashi, Hyogo Prefecture) Nishi-Kobe Works (Kobe, Hyogo Prefecture) Kawasaki Precision Machinery (U.K.) Ltd. (U.K.) Wipro Kawasaki Precision Machinery Private Limited (India) Kawasaki Precision Machinery (Suzhou) Ltd. (China) Kawasaki Chunhui Precision Machinery (Zhejiang) Ltd. (China) Kawasaki (Chongqing) Robotics Engineering Co., Ltd. Flutek, Ltd. (Korea)
	• Hydraulic presses	Kawasaki Hydromechanics Corp. (Akashi, Hyogo Prefecture)

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Kawasaki Green Product Promotion Activity

To achieve our group mission, “Kawasaki, working as one for the good of the planet,” we promote Kawasaki Green Products and Kawasaki Super Green Products inside and outside Kawasaki. These products meet the criteria originally established by Kawasaki to assess the conformity of products regarding environmental performance and environmental management in manufacturing processes.

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