RESEARCH INTRODUCTION

In pursuit of engines with improved fuel efficiency

About the fan of a jet engine

Turbojet engines and turbofan engines are the two main types of jet engines widely used in aircraft nowadays, providing propulsion by expelling a jet of exhaust gas toward the back. With the turbojet engine, all air taken into the engine passes through the combustor and is expelled as a jet. Therefore, the exhaust gas of a turbojet engine is characterized by a high temperature and a high velocity. The thermal energy and kinetic energy remaining in the exhaust gas after it has propelled the engine forward are wasted. With a turbojet engine, there is a large amount of this waste. Better performance (propulsive efficiency) can be achieved by lowering the temperature of the exhaust gas as much as possible while also reducing the exhaust speed so that it is closer to the flight speed. With the aim of reducing the temperature and speed of the turbojet engine exhaust, the turbofan engine was designed to provide a lower average temperature and reduced speed of the exhaust by positioning a large-diameter fan at the front (visible when the engine is viewed from the front) and ejecting (bypassing) some of the air sucked into the engine so it does not pass through the combustor (fig. 1).

The ratio of the bypass airflow (air that does not pass through the combustor) to the core airflow (air that passes through the combustor) is called the bypass ratio. As the bypass ratio increases, the average temperature and speed of the exhaust gas decrease and the propulsive efficiency improves, resulting in better fuel efficiency. Nearly all modern civilian jet civil transport aircraft are equipped with high-bypass turbofan engines.

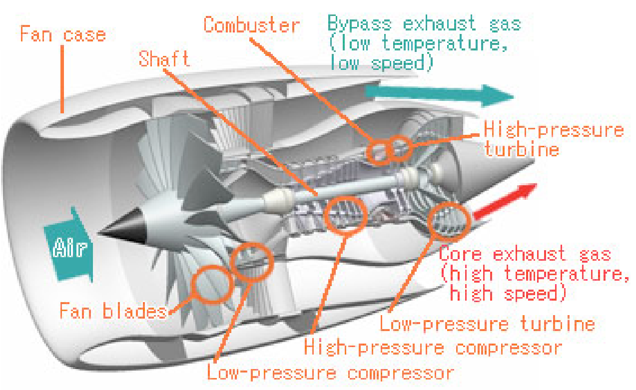


Fig. 1: High-bypass turbofan engine

Relationship between fans / compressors and engine weight

With fans and compressors (the latter positioned behind the fan and increasing the air pressure) being essential factors in determining the "overall pressure ratio" (ratio of the pressure at the fan inlet and compressor outlet), which is a key variable for determining the engine cycle efficiency, raising the overall pressure ratio more efficiently affects the fuel consumption rate directly. The trend with recent turbofan engines is toward further increasing this overall pressure ratio with regard to fuel consumption. Since fans and compressors move air in the adverse direction from a lower pressure to a higher pressure, it is difficult to increase the pressure all at once. In response to this, compressors are arranged in line and in multiple stages to gradually increase the pressure. Therefore, a higher overall pressure ratio will inevitably result in an increased number of fan and compressor stages, which leads to increases in weight and the number of parts. While the weight and number of parts for fans and compressors in current turbofan engines already account for a significant proportion, increasing the overall pressure ratio in an attempt to improve fuel efficiency will lead to a greater increase in engine weight. As a result, we are faced with the dilemma where efficiency improvements are offset by this increase in weight. At the same time, an increase in the number of parts also raises the total cost of ownership (TCO), for example, due to longer processes and higher costs, from the production to assembly and maintenance of the parts.

Ongoing research

At JAXA, in order to resolve these conflicting issues concerning fans and compressors, we have started research to reduce the weight and number of parts while improving the overall pressure ratio by increasing the pressure ratio at each fan/compressor stage (high loading) and to improve the overall efficiency of the engine. With this higher loading design, it is difficult to maintain a high efficiency-for example, the flow easily separates since the airflow must overcome an even higher adverse pressure gradient, as described above-and there is a general tendency toward reduced margins of the stable operating range when it comes to unstable phenomena, such as stall and surge(*1), characteristic of fans and compressors. In order to utilize the higher loading of fans and compressors while maintaining high efficiency and stable operation, we must first address these issues. To do so at the production level, a fan/compressor test facility (fig. 2) for testing isolated fans/compressors has been set up, and a research fan (fig. 3) has been designed and built to be tested at this facility. The fan is has been designed mainly using computational fluid dynamics (CFD). This is a high loading transonic fan with a 50 cm diameter equivalent to the fan of a turbofan engine with a thrust of 1 ton. An advanced three-dimensional blade shape is adopted to achieve a high efficiency, reduce loss, and weaken the shock waves(*2) generated near the blade tip due to the tip circumferential velocity of Mach 1.3 (1.3 times the speed of sound), which is required in order to obtain a high pressure ratio at the design point. Using this research fan, we expect to conduct studies to increase loading and efficiency of fans and compressors, enlarge the stable operating range, and reduce noise, which has gained attention due to the recent increased interest in environmental issues.

(*1) Surge: The blades of the compressor stall, and performance is lost due to a disruption occurring in the compressed airflow.

(*2) Shock wave: Loss associated with a wall of high-pressure air generated by a body (the blade tip in this case) that moves through a medium, such as air, at supersonic speed

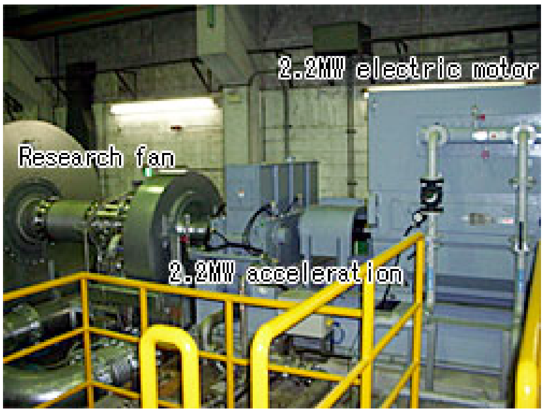


Fig.2 Fan / compressor test facility

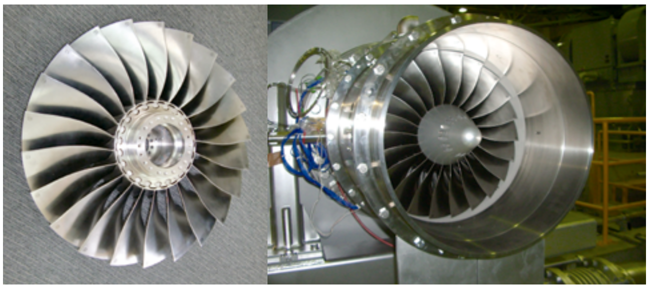


Fig.3 Fan blade shape (left) and research fan

[Jet Engine Technology Research Center]

Daisaku Masaki

R E S E A R C H
INTRODUCTION

Lightweight construction made safe

Making engines lighter

Since aircraft fly resisting gravity, it is desirable to make them as light as possible. In order to make aircraft lighter, "carbon fiber reinforced plastics" (CFRP)[*1], which are lighter, stronger and more corrosion-resistant than conventional metal, are being used on the wings and fuselage. Since, unlike metal, CRFP does not rust, it is being considered as a means to "reduce maintenance costs". In recent years, CFRP has also started to be used in the fan system (fan case and fan blades) for large aircraft. This is an application of CFRP that is being expanded.

Although we would like to use CFRP in the fan system for medium and small aircraft, the dimensions of the engine are smaller, therefore the thickness of each component is thinner. The thinner material thickness has raised issues concerning the strength of CFRP. Therefore, we are embarking on research with the aim of utilizing CFRP in the engine fan system for small and medium aircraft.

Safety first

In January 2009, a passenger aircraft was ditched in the Hudson River, which flows on the west side of New York City (USA). This event, called "Miracle on the Hudson", ended with no fatalities due to the good judgment of the captain and was heavily covered in the news at that time. The cause of this accident was determined to be engine failure as a result of a "bird strike".

The cause of this accident was determined to be engine failure as a result of a "bird strike". When a bird is ingested by an engine, the fan blades at the front of the engine are damaged. As a result, fan blades are fragmented and scattered, causing damage to the fan case. Since the engine is located near the fuselage (the section where passengers sit), it would be disastrous if blade fragments pierced the fan case. A bird flies into an engine at the flight speed of the aircraft, and fan blades rotate at a speed near that of sound. Therefore, a bird can collide with fan blades at a speed of about 400 m/s. In such a situation, scattered blade fragments would collide with the case at the same speed. Numerous safety designs have been incorporated into currently operating aircraft so that damage does not extend beyond the fan case even if a bird strike occurs. In order to adopt a new material for aircraft, we must demonstrate that safety is not compromised by the material. The properties of CFRP vary depending on the types of resin and carbon fiber as well as the arrangement of fibers.

Therefore, in order to collect basic data on the characteristics of CFRP laminates under a high-speed projectile impact, tests were performed simultaneously at Nagoya University and Ehime University by impacting each test piece with steel balls, which represent blade fragments (fig. 1). The combination of a unidirectional fiber arrangement and a resin which has low fracture toughness[*2] absorbed the most impact energy by distributing the impact force of the steel ball and spreading the damage.

In order to assess the validity of the test data and to determine the most suitable CFRP, we are developing a numerical simulation code (program). Figure 2 shows the simulation results of the program being developed. The simulation results also demonstrated that the resin which

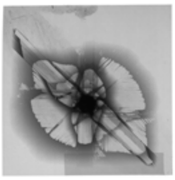
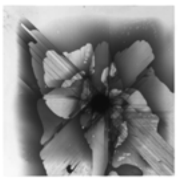
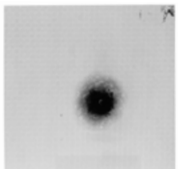
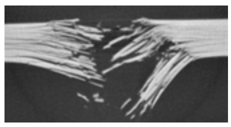
Planar view			
Cross-sectional View (Plate thickness: Approx. 2 mm)			
Prepreg type	Unidirectional	Unidirectional	Woven
Resin fracture toughness	High	Low	High
Speed (m/s)	192	191	191
Results	Not penetrated	Not penetrated	Penetrated

Fig.1 High-speed projectile impact characteristic test

has low fracture toughness absorbed the most impact energy, and the simulation revealed the mechanism of such results.

A program for materials development

Our goal is a versatile simulation program that is able to determine CFRP properties suitable for an engine fan. Therefore, we are continuing research in collaboration with IHI, a corporation which has proven experience in turbofan engine development.

The simulation program described above focuses on impact events between hard objects: blade fragments and the fan case. However, objects flying into an engine are usually soft bodies, such as a bird. Moreover, fan blades are held by a shaft at only one edge, therefore large deformations easily occur. The analysis of the impact of a soft body on an object which is supported flexibly is more difficult than that of an impact between hard objects, and the simulation program becomes more complex. Currently, we are also developing such a simulation program.

By using these programs, we will be able to determine the most appropriate CFRP for a fan system. With the aim of establishing the technology necessary to utilize CFRP in the engines of future small size and medium size aircraft, we are continuing research through close cooperation between industry, government and academia.

(*1) Carbon fiber reinforced plastics (CFRP): Materials which consist of a combination of more than two materials with different properties are called composite materials. Composite materials can possess more desirable properties than those of each individual material. CFRP is a composite material that combines the stiffness and strength of carbon fiber with the light weight of resin. They are formed by stacking sheets of "prepreg" (carbon fiber impregnated with resin) into the desired shape, then curing it under a high temperature and high pressure. There are various types of prepreg, such as "unidirectional prepreg" (where the fibers are aligned in the same direction) and "woven prepreg" (where the fibers are woven like garment cloth), each with different properties.

(*2) Fracture toughness : Toughness of the material

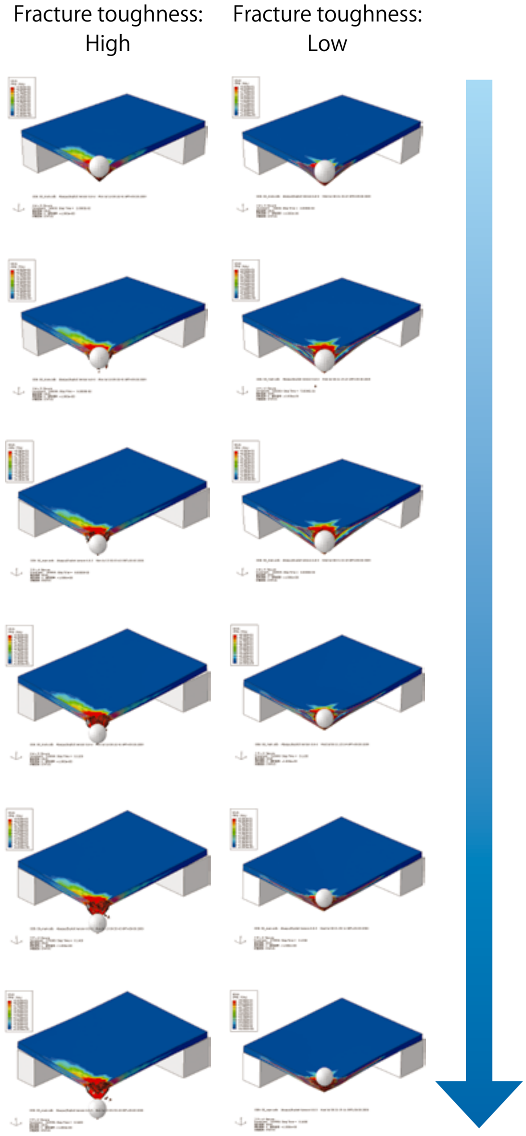


Fig.2 Numerical analysis results

[Advanced Composite Group]

(from left) Toshio Ogasawara, Akinori Yoshimura

Fans — Large impellers at front of engines

■ Structure of a jet engine

The purpose of a jet engine is to propel the aircraft. The force (thrust) to propel the aircraft is determined as a product of the "volume of air" sucked into the engine and its "exhaust velocity". The best way to increase thrust is to increase as much as possible the amount of air sucked in and increase as much as possible the speed of the exhaust.

The air sucked into a jet engine is compressed by a "compressor". The compressed air is mixed with fuel in the "combustion chamber" and ignited to reach a high temperature and high pressure. The air at the high temperature and pressure passes through the "nozzle" and is vigorously expelled. Air that has passed through the combustion chamber and built up energy is used to drive the compressor. After the combustion chamber, there is a "turbine" on the same shaft as the compressor, which is driven by the air turning this turbine (fig. 1)..

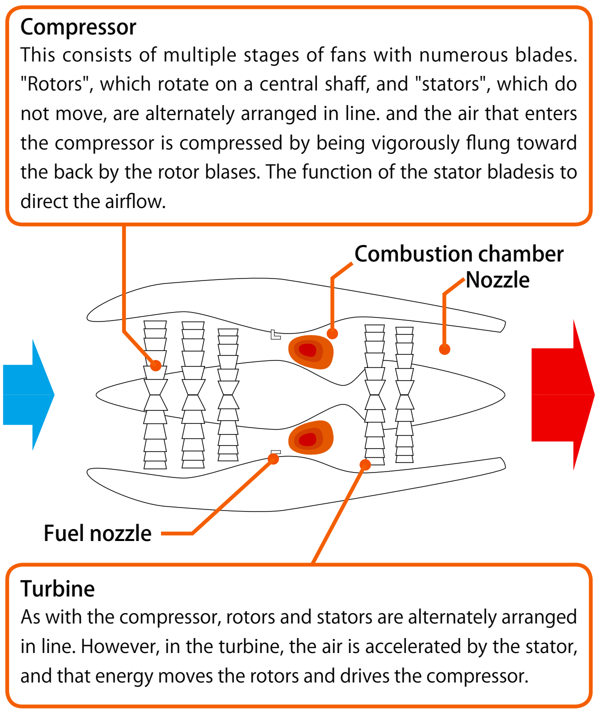


Fig.1 Jet engine

■ Importance of propulsive efficiency

What is expected of a jet engine?

This differs depending on the purpose and situation in which the aircraft is used. For airline companies in the business of transporting passengers and for us consumers using them, the main appeal is a "drastic reduction in operating costs".

Most airliners fly at a speed of 0.8-0.9 times the speed of sound (Mach 0.8-0.9). The propulsive efficiency (fuel efficiency) increases when the flight speed of the aircraft and the engine exhaust speed are the same. However, if a simple jet engine was installed on a passenger aircraft, the fuel efficiency would become worse since the air would be expelled at such a high speed that it would exceed the speed of sound. One may think that this could be improved by reducing the exhaust speed; however, simply reducing the speed would not provide enough thrust. This is why the "fan" was devised.

A fan can suck in a large amount of air with a large impeller installed at the front of the engine. The compressors are driven by different turbines (Refer to page 1, fig. 1).[*] With some of the air that passes through the fan bypassing the combustion chamber and simply being expelled, the overall exhaust speed can be reduced when this air is combined with the core exhaust gas. In turbofan engines of recent years, a higher bypass ratio has been pursued, where the airflow through the fan is vastly increased in relation to the airflow through the core, in order to improve fuel efficiency.

Many other methods to improve fuel efficiency are being considered. For example, there is the method of increasing the overall pressure ratio, which is the ratio of the pressure at the intake and outlet. (Refer to page 1) In modern turbofan engines, the balance between the propulsive efficiency and overall pressure ratio is being improved, and the fuel consumption is being reduced. In addition, there are other important factors, such as reducing weight, improving reliability as well as reducing the environmental load and maintenance costs.

■ Environment also a key factor

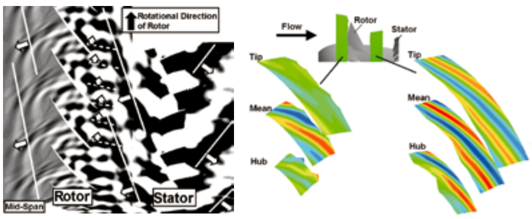
In recent years, "environmental friendliness" with regard to air transportation has gradually come to the forefront. In order to improve environmental friendliness without compromising performance or safety, JAXA is embarking on the "development of clean engine technology".

In response to airport noise regulations and in order to reduce noise inside cruising aircraft, lessening the noise generated by aircraft has become an important issue. There are various sources for the noise generated by an aircraft, but the noise from the jet engine is certainly one of them. Noises of particularly high levelsE are those generated by the fan and those generated by the exhaust jet. We are continuing research through testing and numerical analysis in order to reduce these noises.

Although already at lower than regulated levels, air pollutants, such as carbon dioxide (CO_2) and nitrogen oxides (NOx), are being emitted by jet engines. When compressed air and fuel are mixed and ignited within the engine, fuel efficiency improves and CO_2 is reduced if combustion gases are at a high temperature and pressure. However, when combustion gases are at a high temperature and pressure, NOx rapidly increase. Therefore, we are proceeding with research and development of technology to improve fuel efficiency and suppress NOx emissions.

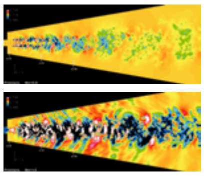
Current turbofan engines are extremely efficient and environmentally friendly; however, we are also tackling technology development of electrically driven fan systems with the aim of improving environmental friendliness.

(*) The compressor in the turbofan jet engine in fig. 1 on this page has a two-stage construction. The fan and low-pressure compressor are driven by the low-pressure turbine, which rotates more slowly, and the high-pressure compressor is driven by the high-pressure turbine, which rotates faster.

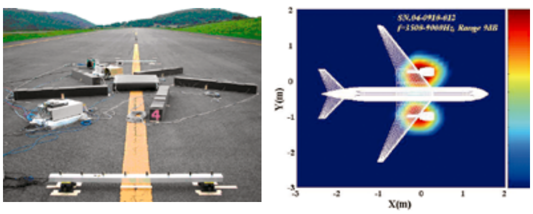


(Left) Numerical analysis results where noise generated by fan stator blades is propagated upstream and downstream
(Right) With further treatment of these results, we are able to obtain a detailed image of the sound wave near the fan.
Research results obtained in collaboration with IHI

Pressure distributions from behind nozzle outlets at subsonic speed (Mach 0.9) and supersonic speed (Mach 1.5); (Top) With a subsonic jet, concentric sound waves are produced near the nozzle outlet. (Bottom) With a supersonic jet, a strong sound wave directed downstream is produced.

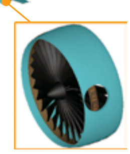


Using equipment for testing high temperature and high pressure combustion, research is continuing to reduce the amount of air pollutants emitted.



In order to reduce noise, it is important to examine what produces the sounds. Therefore, we are performing tests with a microphone array to identify the source of sounds.

Research is continuing to develop technology for an extremely lightweight electric fan system connected to a power source, such as a fuel cell, using electrical wiring. Since the fan and drive system are not connected by the same shaft, the fan orientation can freely be changed.



[During takeoff] With exhaust expelled backward at an angle, the aircraft can take off within a short distance.

[During high-speed cruising] Since all fans are no longer needed while the aircraft is flying at a high speed, folding up some fans can reduce the resistance added to the aircraft and improve efficiency.

Fig. 2: Various JAXA research and development projects