A Study on the More Electric Architecture for Aircraft and Propulsion (MEAAP) Concept

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The use of more electric aircrafts will improve safety, ecology and economic benefits through innovations designed to integrate their power and thermal management. Under this concept, high power generation is the crucial issue. The More Electric Architecture for Aircraft and Propulsion (MEAAP) consortium is working with IHI to exploit the electrification system for future engines and aircrafts over the next decade or two. This paper introduces the latest resolution approach developed by IHI and the results of Japanese interactive open innovation.

1. Introduction

The electrification of aircraft has advanced as a way to reduce environmental load and increase cost efficiency(1). However, we have heard that airlines expect further improvement of operability (engine responsiveness) and maintainability, and achieving environment-friendly operations by minimizing noise and exhaust gas(2). The progress of aeronautical technology is a human challenge to ensure safety(3), and the electrification of aircraft plays a part in that challenge. Extending and developing aircraft electrification and expanding systems not only contribute to the optimization of energy, but also eliminate the need for complicated hydraulic systems, pneumatic systems and mechanical mechanisms for energy supply, thus improving design freedom and maintainability, and making it possible to reduce aircraft mass. Improving design freedom makes it easier to build multiplex systems and enhances the reliability of safety as the basic and universal requirement for aircrafts(4). Moreover, a fast torque response, being able to know the torque generated accurately, and the ease of distributing power sources, which are characteristic of electric motors, are three factors(5) that have the potential to meet all expectations of airlines as they improve aircraft controllability. However, from a wider point of view, in the age when automobile electrification is already making the leap to flying cars(6), commercial aircraft has become an area that is left out from the development of electrification in mobility. The Boeing Company (USA)'s 787 airliner is equipped with electrically powered pressurization and air-conditioning systems, while Airbus (France)'s A380 airliner is equipped with a high-power electric steering system and an electrically powered thrust reverser drive system. When these aircrafts entered the market, the world expected the introduction of aircraft electrification to rapidly grow(7). However, in reality, there has been no emergence of new electrified aircraft since then.

To lead the paradigm shift to the new electrification of commercial aircrafts, it is necessary to build integrated networks that can be used for aircrafts, engines, and aircraft systems, and to further develop the assessment of electrification and analyze engines and aircrafts in an integrated manner(8). The challenge faced in expanding the field of aircraft electrification is that for engines that serve as the node between an aircraft and an electrified aircraft system, it is necessary first of all to solve the problem with the power source of both, the propulsion/primary power and the power plant/secondary power. The following items have been pointed out regarding that issue(9), (10).

(1) Challenges on the engine side:
- Effects on engine operability due to an increase in extracted horsepower
- Increase in damage to the gear box of the engine
- Resonance between large-capacity generators and shaft systems

(2) Challenges on the generator side:
- Increase in loads on exhaust heat systems with increasing heat generation and consequent reduction in fuel efficiency
- Problems with mass, assembly and maintainability due to upsizing, and increase in air drag due to enlarged front areas of engines
- Rotor dynamics design that considers the couple with engines
- Application of new technologies that have no field experience of being used aboard aircraft such as permanent magnet generators

In other words, in addition to downsizing, weight reduction and cost reduction, which are common issues for mobility, the installation of engines for large-capacity generators and solving the management of increasing exhaust heat are two important major challenges in aircraft application.

In the 2010s, IHI started conducting a research to promote the electrification of aircraft engines More Electric Engine (MEE). We have proposed the shift to low-pressure spool power generation from high-pressure spool power generation in conventional aircraft engines to solve the problem of engine operability and continued our research on engine control(11). To make it possible to apply permanent magnet power generators, which are expected to have a high power density, to aircrafts, we presented shutdown techniques using simple circuit logics as the technology to shut down power generation as a safety measure in the event of a failure, which is a specific issue faced in this application(12).

This paper discusses the technology development for the various remaining challenges from the three following points of view and proposes the vision to achieve electrification by solving them.

① Structures to carry large generators aboard
② Heat sinks and heat exhausting methods
③ Control of increase in generation capacity

2. Structure to carry large generators aboard

It is obvious that there are various challenges in the present structures to carry generators aboard due to an increase in extracted horsepower. As a result of the increase, it may be difficult to ensure the feasibility of the mechanical structure that divides the power from the engine rotating shaft with the gear in the engine and allows the power to transfer outside using the rotating shaft, and then distributes the power at the accessory gear box and drives the generator. In contrast, it can be easily assumed that the method of generating power without going through the extracting power shaft and gear box can be a fundamental solution. In other words, it is a structure that directly connects the engine shaft. In this case, the generator can be placed in front, inside, or at the rear end of the engine. If the generator is placed in front, the struts to secure the generator will create air drag; if the generator is placed inside the engine, the engine will need to be disassembled to conduct maintenance on the generator, so neither is appropriate.

On the other hand, placing the generator at the rear of the engine is not considered in the advanced research example because there are technologically difficult challenges that need to be solved with the heat resistant insulation of the generator that generates its own heat in the turbine downstream section that can reach a high temperature. At the same time, the mechanical performance requirements of the generator as an engine component that is directly connected to the engine as well as the constraints of heat exhaust design also need to be met.

2.1 Engine embedded electric machine (E3M)

Electric motors and generators mounted inside the tail cone are located in the rear of the engine low-pressure turbine. The concept for the engine embedded electric machine is shown in **Fig. 1**. As mentioned earlier, this section can reach a high temperature, but it is difficult to adopt water-cooling because the engine can be exposed to extreme cold in some cases when it is used in cold climate areas. Therefore, for engine embedded electric machines (including generators), the heat is released by using engine oil as is the case with the cooling of engine bearings. From an operational point of view, it is necessary to assume that the engine oil will reach a temperature that is higher than 100°C. Having electric motors and generators that can withstand cooling using this oil, particularly heat-resistant films of winding, is an important challenge. To solve this, IHI has developed a high heat-resistant insulating film in cooperation with Sumitomo Seika Chemicals Co., Ltd. The heat-resistant performance has been drastically improved on the winding, so it can also significantly improve heat exhausting capacity even for machines that have to use high-temperature fluids as coolants.

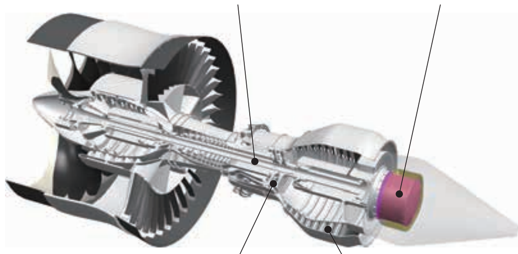

Fig. 1 Concept for the Engine Embedded Electric Machine (E3M)

2.2 Improvement of heat resistance

This heat-resistant insulating film with improved heat-resistant performance uses Toughclaist® as the basic material, which was jointly developed by Sumitomo Seika and the National Institute of Advanced Industrial Science and Technology. In this paper, we developed the coating for electrodeposition films on the assumption that the film is applied not only to shaped and jointed Armature windings in electric motors and generators, but also to conductors such as bus-bars of high-power wiring. As a production technology to increase quality stability in anticipation of practical use, this paper proved that the coating provided heat resistance of 300°C or higher for 1 000 hours or longer while being electro-deposited to conductors in an evaluation conducted in cooperation with SUNCALL CORPORATION. Moreover, as a production technology that is required for electric motors and generators to achieve practical use, we are proceeding with the construction of systems with the processes being evaluated by SINFONIA TECHNOLOGY CO., LTD.

As a step-up of the development for the practical use of large-capacity electric motors and generators, we evaluated the application of these technologies in stages by using small models in anticipation of extended application to medium-sized electric motors to be used in aircrafts. A high-density shaped and jointed winding technology is required for medium-to-small sizes in this technology field, so we applied it to the shaped and jointed winding that is produced in cooperation with Aster Co., Ltd. from the "Research and Development of High-Density and High-Power Motor with Shaped and Jointed Armature Coil Made by Aster," a strategic energy-saving technology innovation program by the New Energy and Industrial Technology Development Organization (NEDO), and generated three-phase current of approximately 100 A using a stator of approximately 110 mm in diameter and approximately 130 mm in length and demonstrated that it can be operated at a winding temperature of 300°C. **Figure 2** shows a high heat-resistant film shaped and jointed winding and a high-density electric motor stator to which highly heat-resistant varnish is applied, and **Fig. 3** shows the results of the generator test of the high heat-resistant film.

The development of the heat-resistant insulating film mentioned in this chapter was commissioned by the "Research and Development of Next Generation More-Electric Engine System" of NEDO's Research and Development Project for Advanced Aircraft Systems toward Practical Application.

3. Heat sink and heat exhausting method

The heat exhaust of a conventional aircraft is limited to the heat exchange with ram air (the air taken in by the pressure forced in by air resistance) or the heat exchange to fuel aboard and engine fan discharge air. The increase in the heat exhaust of the system not only increased air resistance and reduced engine fuel efficiency, but also increased mass and deteriorated maintainability because heat needs to be transported to heat sinks (air and fuel) in limited locations. Electrification is done to reduce weight and improve maintainability, and airlines regard this contradiction as an important point to be improved. SHIMADZU CORPORATION and IHI are dealing with these problems by linking the air-conditioning system that releases a large amount of heat from the aircraft with the engine system[13].

Moreover, IHI also contributes to increasing the capacity of generators by acquiring new sources to exhaust heat (heat sinks) and new heat exhaust methods by researching autonomous air-cooling systems and electric fuel systems.

3.1 Autonomous air-cooling system (AACS)

The autonomous air-cooling system has the same principle as that of forced-air-cooling systems in general, but it is characterized by its small, light-weight and high-efficiency cooling system, which is applicable to airborne power electronics. **Figure 4** shows the concept for the autonomous air-cooling system. The challenges in releasing heat from high-density heat elements (dies of power semiconductors) that are unique to power electronics were applying small, high-density heat sinks and downsizing the blowers to send a large amount of air into heat sinks. In cooperation with Sumitomo Precision Products Co., Ltd., IHI demonstrated an air-cooling system for both non-pressurization and pressurization by assuming the use of an Insulated Gate Bipolar Transistor (IGBT) module of 10 kW or larger. **Figure 5** shows a high-speed electric blower (100 000 rpm), for which we used a 100 000 rpm level for design. We also developed a new super-small gas bearing and applied it to the blower.

Going forward, we will contribute to higher heat exhaust efficiency by applying dispersed cooling to large-capacity power generation systems through research and development aimed at large power module applications.

3.2 Metering-integrated fuel-feeding electrification (Mifee)

The electrically powered fuel system that our company proposes drives a fuel pump of gear-pump and fixed-volume type with an electric servomotor and controls the fuel flow required by the engine with motor rotation speed. This technology eliminates the need for precision instruments that

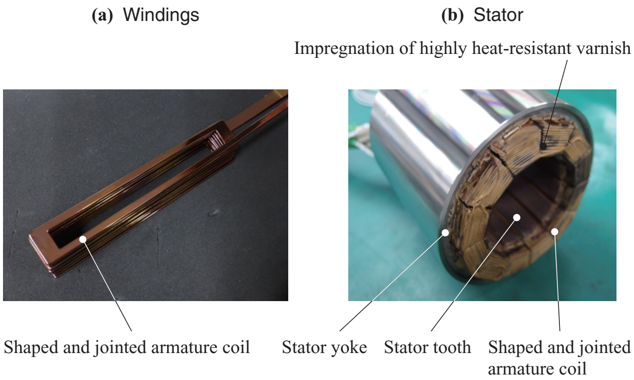

Fig. 2 High-density electric motor stator with high heat-resistant coating coil

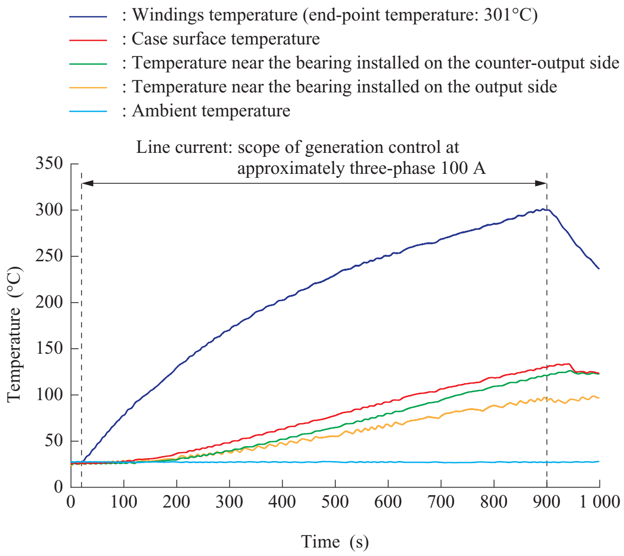

Fig. 3 Results for the 100-A generator test at 300°C

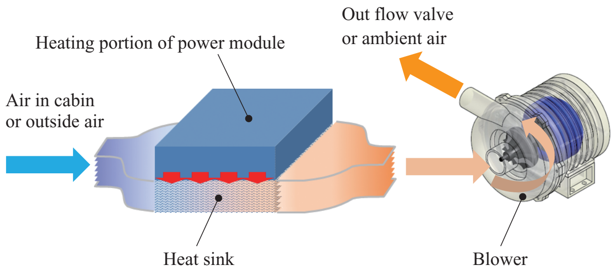

Fig. 4 Concept for the Autonomous Air-Cooling System (AACS)

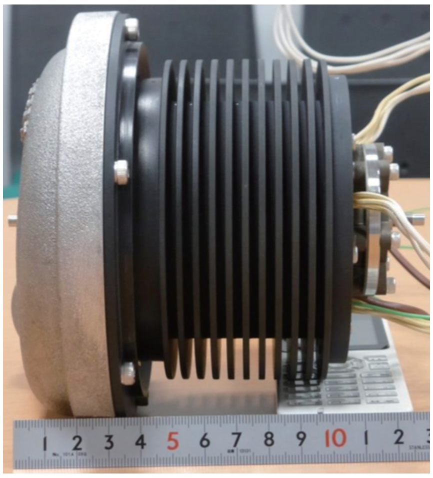

Fig. 5 100 000 rpm electric blower

are composed of many hydraulic components (such as valves), and advantages can be expected in terms of maintenance and cost. Moreover, there is no excess fuel circulation and engine extracting power can be reduced, so specific fuel consumption is expected to be improved with better fuel system efficiency[12]. Minimizing temperature rise by fuel circulation can improve engine heat management and the heat exhaust performance of fuel heat sinks.

In this system where the fuel metering unit is removed, IHI demonstrated using a rig test that low-speed rotation of low flow when the engine is started and high-speed rotation of high flow can be controlled using the gear pump of the motor direct drive, and the fuel flow required for the engine can be controlled simply with motor response and rotation control accuracy. **Figure 6** shows the rig test for metering-integrated fuel-feeding electrification, and **Fig. 7** shows the concept for electric gear pump mechanism.

Going forward, we will promote the efficient use of fuel heat sinks and contribute to the extension of heat exhaust systems for large-capacity power generation systems by integrating engine heat management with aircraft thermal management.

4. Control of power generation capacity

The electrification of many systems and machines, including

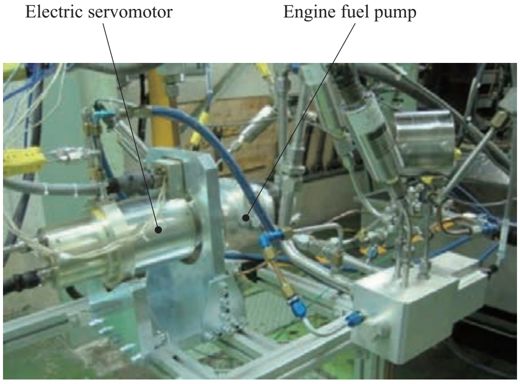

Fig. 6 Test rig for Metering-integrated fuel-feeding electrification (Mifee)

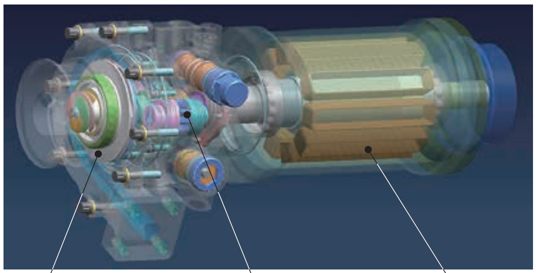

Fig. 7 Concept for the electric gear pump mechanism

Flight Control Systems (FCS), will be promoted and electric power demand will be further increased. The Boeing 787 that was already electrified has a power generation capacity that almost reaches 1.5 MW. The optimization of demand and supply by making the power supply and distribution for future aircrafts efficient is a challenge faced in achieving mass control. However, even though integrated management of electric power is necessary, the increase in peripheral equipment aimed at greater functionality has to be controlled because higher priority is given to the mass, cost, and reliability aspects of the aircraft as a whole. The research[14] of Nabtesco Corporation and IHI share the common concept of introducing a distributed power generation system that can optimize power demand and supply and improve aircraft maintainability with a focus on a strong and flexible (resilient) DC power bus system that can be easily connect the power bus in aircrafts to distributed power sources and conduct cross-feed between buses.

Moreover, we found out from reports of airlines from workshops that when they tackled this challenge further from the point of view of engines, the high torque response that is unique to electric motors causes sudden torque fluctuation to the engine and its transfer mechanism in reaction, which may lead to adverse effects[15]. The electric motors used are made of both motors and generators, so the powerback from the aerodynamic rudder causes the current to flow back to the power source side as energy regeneration, and the current that has nowhere to go suddenly causes an excessive voltage rise. IHI has tried to construct power bus systems that make use of flywheels to absorb short-period fluctuations in power demand. Initially, we planned a centralized control system that scales down the performance for industrial use. However, to meet the expectations of users within a realistic period, we shifted to small, distributed flywheel systems that have relatively low risks.

For this flywheel system (CFS), we assumed approximately 3 kg of mass and 3-kW actuator driving power. The flywheel is composed of an electric motor that is coaxially driven by a single rotor shaft and a generator. **Figure 8** shows the concept of a small flywheel system. The controller of the generator supplies current in response to the demand from the actuator, and the controller on the electric motor side supplies current from a power bus at a low time constant. If there is a sudden large current demand from the actuator, the

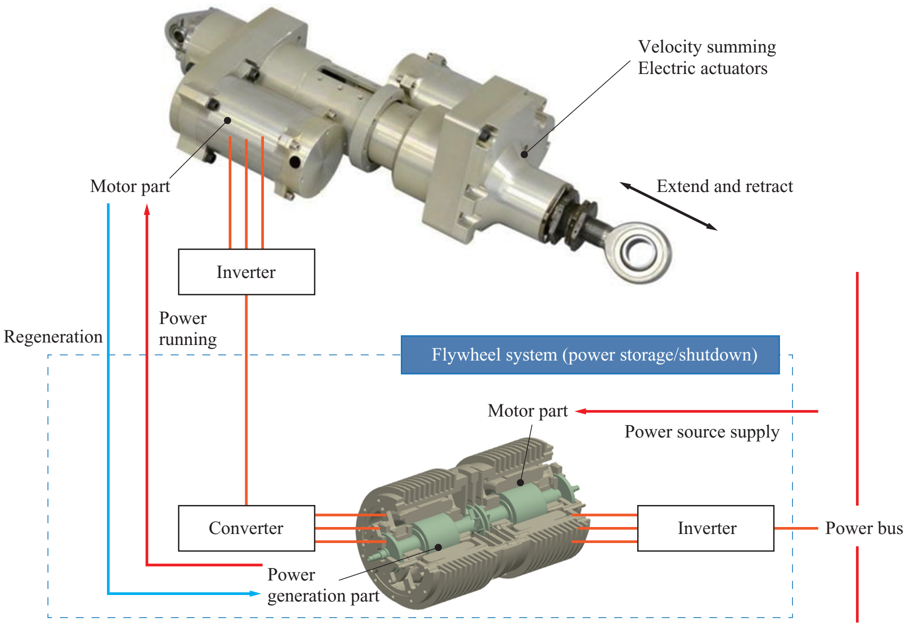

Fig. 8 Concept for power management in the flight control system

generator instantly supplies current from the kinetic energy of rotors (flywheel effect). On the other hand, in the case of a powerback from the actuator, the generator accelerates the rotor as a motor and absorbs the current as kinetic energy.

The two insulated stators of the flywheel system can increase or decrease the power bus voltage and actuator supply voltage by changing their specifications. As the power bus and the load side are mechanically separated, they also play a role in preventing failures from spreading. This system realizes a compact device for converting between high-density kinetic energy and electric energy with low maintenance by applying the high-speed rotation and small air-cooled motor technology that was developed as part of the dispersed air-cooling system to increase the power density and by eliminating the low power storage loss function of flywheel batteries in general. **Figure 9** shows the cascaded flywheel system mechanism (concept).

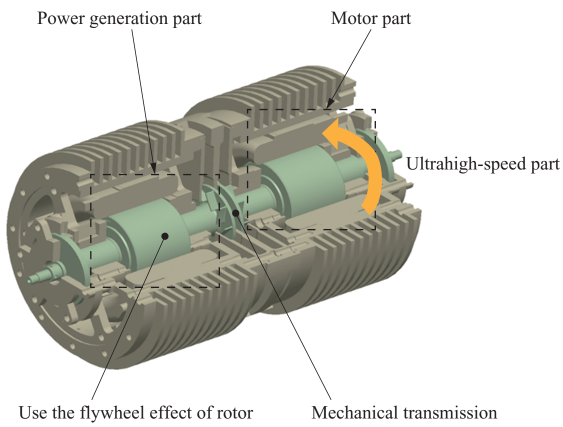

Fig. 9 Concept for the Cascaded Flywheel System (CFS) mechanism

5. Future of the system

5.1 From optimization of energy to improvement of reliability

Integrating the power of aircraft systems into electric energy provides values that are not limited to the improvement of general energy management and maintainability in various leading industries. As dispersed driving sources, motors control the structural mass of riggings with their design freedom and contribute to the minimization of fuel consumption. In aircrafts, exhaust heat is converted into the mass load and air drag of aircrafts, which are then further converted into fuel consumption, so controlling exhaust heat is important. Efforts to dispose of heat by sending it the cabin air that is released outside aircrafts and to the fuel that is consumed by engines also reduce air drag caused by ram air taken in, which contributes to higher fuel efficiency. **Figure 10** shows an example of an electric aircraft system.

Aircraft manufacturers have pointed out that commercial aircrafts have not achieved the level of the System of Systems (SoS), which connects systems in a sophisticated manner to achieve the integration sought by electrification. To solve this, it is necessary to have software technologies to accumulate sophisticated control technologies with clear and concise logics, while supporting the improvement of system reliability with a multiplexed system by improving the reliability of machines and downsizing them as hardware technologies become more advanced. Acquiring both types of technologies will be sufficient to create aircraft systems that can win the ultimate trust of users based on high reliability and safety(3) at which Japanese industrial products have always excelled.

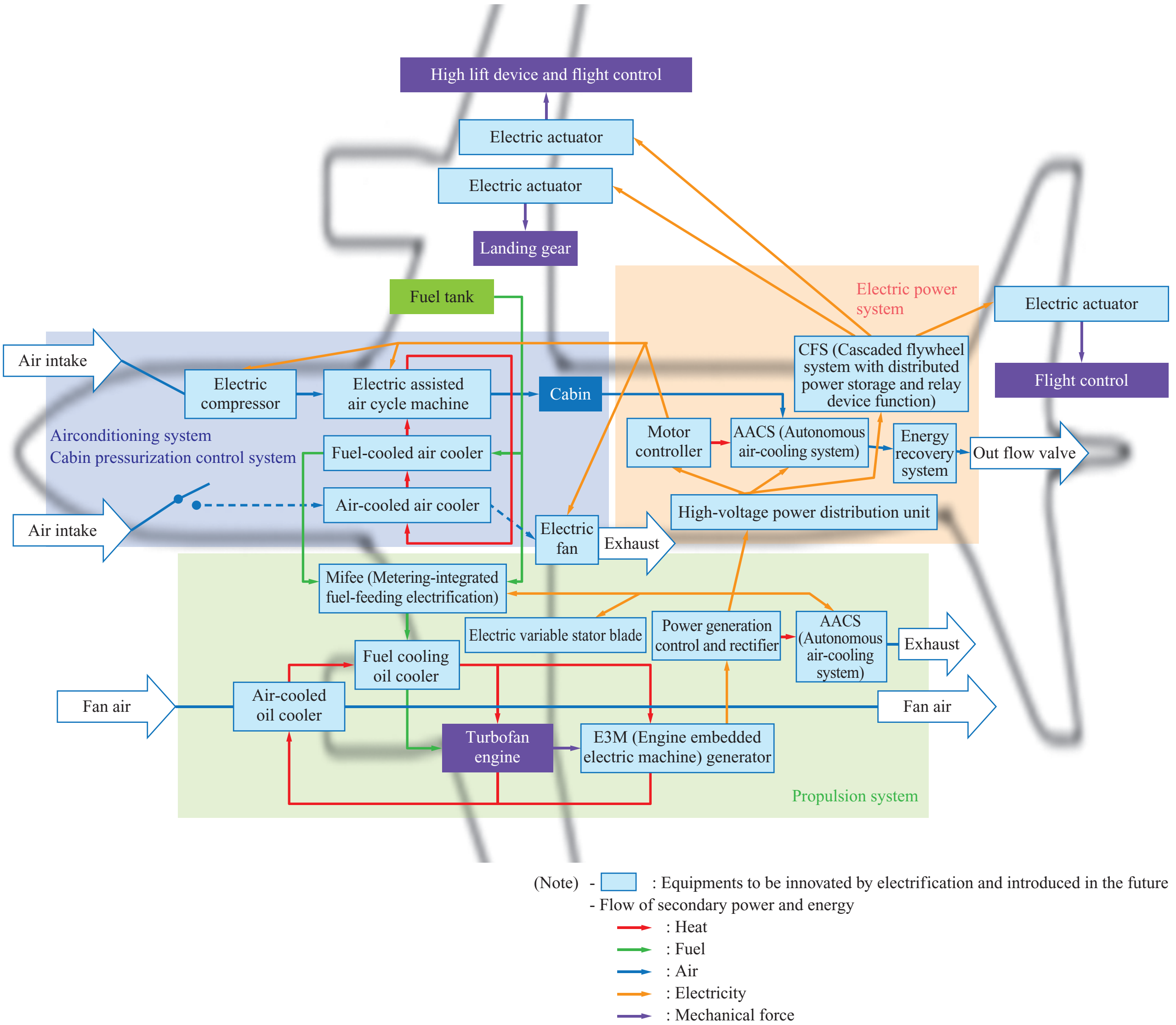

Fig. 10 Example of an electric aircraft system

5.2 Improvement of maneuverability and minimization of noise and exhaust gas from the optimization of energy

The ultimate direction to fully utilize the effect of aircraft electrification lies in electric propulsion. The emergence of future power sources (such as high-density secondary batteries and refuelable primary batteries or fuel cells) can truly push CO_2 reduction forward. However, when looking at the continuity of technology development, it is important to have a system concept that allows technologies that are being developed, meanwhile being deployed with practical use, instead of depending on unreliable and non-continuous technology innovations. That is the reason why turbo-electric propulsion, which does not leave its future to the development of battery technologies, is gaining more attention among electric propulsion systems. However, even though the system is designed to supply electric power from a large gas turbine generator aboard aircrafts to electric fans, there are many problems, such as the modification of aircraft structures including distributed fans, and the concept of integrating propulsion units into aircrafts (for example, creating a boundary layer ingestion fan that is expected to reduce the frictional resistance of aircrafts by installing propulsion units in the rear of the fuselage and actively absorbing the boundary layers of fuselage surfaces).

As a proposal for a system that focuses on feasibility, the authors plan to provide an electric propulsion architecture to receive and supply energy in various ways while keeping the current aircraft structure intact as much as possible. **Figure 11** shows an example of the concept for hybrid propulsion beyond E3M. The authors also considered using Auxiliary Power Units (APU) as energy boosters of transient propulsion systems, while making use of the aforementioned engine low-pressure-spool and high-pressure-spool generators as electric motors. To improve fuel efficiency and ensure control stability when decreasing engine speed during power assist at the time of take-off or landing and taxiing, it is necessary to design compound systems to mutually receive and supply power. There are many ongoing discussions in the world about the advantages and disadvantages of various

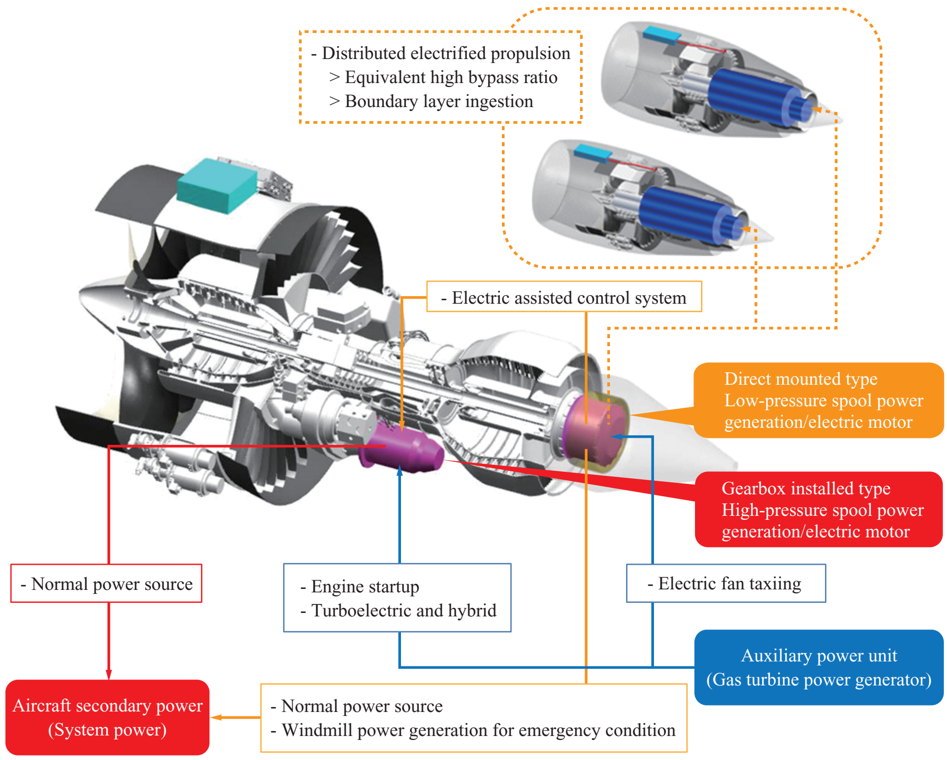

Fig. 11 Example of the concept for hybrid propulsion beyond E3M

styles at the review stage in order to achieve that.

The continuity of system innovation guarantees that well-proven technologies will be passed on to aircrafts that give top priority to safety in the future. Systems that have accumulated actual operation will be further developed, and electrification will be the technology that provides safety, reliability, maneuverability, and maintainability in aircrafts that are kind and friendly for humans and the earth.

6. Challenges to be addressed in the future

6.1 Development of electrification technology

Through the discussions presented up to **Chapter 5**, it is clear that rotating machines are the key technology that is closely associated to the problems of energy and heat in all aspects of optimization and integration of electrification. The extraction of shaft output from gas turbines as power sources, hydraulic and pneumatic technologies as the secondary power, speed increasing/reducing gears as speed control and regulation mechanisms such as valves, and shaft support technologies such as rolling bearings and plain bearings will remain popular technologies, but they are approaching their limits.

The direct driving of engine embedded power generators, ultra-high-speed built-in motor type blowers and fuel pumps that are directly coupled with electric motors is the reason why we are waiting for breakthroughs, such as higher speed, higher power and oil-free rotating machines that meet the demands of aircraft systems with a drastic improvement in speed regulation control through low-loss high-speed inverters and the expansion of the application of bearings as technological support.

With the four dynamics of mechanical engineering at the center, the development of aircraft electrification technologies removes barriers to electric designing; increases competitive strength and speed through the open innovation of magnetic materials, chemical and heat, production technologies and others; and merges them through interdisciplinary engineering.

6.2 Development of systematization technology

The development of complicated and integrated systems mentioned in **Chapter 5** involves an enormous amount of software. Discussions at international conferences held outside Japan pointed out that software development is one of the largest challenges of electrification. Significant human resources and their management, as well as risks of costs and schedules have to be controlled. Engineers of the U.S. Federal Aviation Administration (FAA) commented[16] that many of the barriers in software development were caused in general when development was established by development entities below Level 1 (initial phase) of the software capability maturity model (equivalent to the present Capability Maturity Model Integration (CMMI®)) with RTCA DO-178 (software development assurance process; hereinafter referred to as DO-178) as the certification guideline. In the case of CMMI vs. DO-178, the former provides the improvement guideline and assessment of business activities in general, such as project management and risk management of software system development, and procurement, service and personnel management, whereas the latter refers to the development and integration process for the certification of aircraft software. Therefore, CMMI is not a substitute of DO-178. However, entities in CMMI

Level 2 (managed), 3 (defined), 4 (managed quantitatively) and 5 (optimized) can definitely carry out the DO-178 development processes, and they are considered to be capable of gaining project benefits such as reducing costs, having shorter schedules, and obtaining the trust of the authorities concerned through process visualization, quantification and optimization in proportion to higher levels.

By capitalizing on our experience in DO-178 development processes, IHI is promoting research aimed at innovating the development of aircraft systematization technologies in cooperation with Hitachi Solutions, Ltd. (official partner of CMMI Institute).

6.3 Development of system assessment technologies

Systems and complications in their missions increase the loads of validity assessment and verification (V&V: Validation and Verification), so each task is required to shorten the period and reduce the cost. One way to do that is the effective use of distributed assets (equipment, rigs, simulators, software and human resources), which is a challenge. To overcome this, it is necessary to create the basic architecture that interconnects existing assets located in geographically separated places and that can jointly evaluate specific technology information without taking such information outside at all, while proceeding with parallel development in a distributed manner at the same time.

To address the risk of man-hours for reworking, which will definitely be generated in the process of integration, the use of agile type development with its many development loops is increasing. However, the difficulty of managing the schedule for developing large systems has not been solved, so it is necessary to push for the improvement of production efficiency using the conventional waterfall type development. For efficient implementation, we share in-the-loop simulations (HILC, SILS and MILS) for each level such as hardware, software, models and others in the mission level, with Model Based Development (MBD) as the starting point(17), which is generalized with a V-shaped model verification as a premise. However, integrating each type of energy with only models has remained an academic challenge for many years, and it is necessary to push for a shorter development period by extending the conventional control logic HILS (C-HILS) to energy and power HILS (E&P-HILS), which returns the interconversion of actual electricity, power and heat to simulators.

6.4 Development of technology to improve system reliability

Unlike railway vehicles and automobiles, the top safety requirement for aircrafts is to continue flying, so multiple configuration is required as a design style, and a safe transition state has to be ensured at the same time. As for fly-by-wire and FADEC (Full Authority Digital Engine Control), redundant functions and fault tolerant designs can be achieved through flight critical control. The challenges of redundant design and fault tolerant design of electrified systems are power conversion systems that are unique to electrification and the mechanism and transmission to change the motor output to driving force.

IHI aims to create design techniques that can quickly make up for and restore functions that are lost as a result of a failure so as not to hinder aircraft operations even if electrified systems fail during flights. However, to build compact and safer electrified systems, which cannot be achieved simply with a multiplexed system with redundancy, we have reported the results of our demonstration of ① active-active control and smooth and quick shifting, ② the mechanical and electrical anti-jamming mechanisms of butted and separated sections and ③ fault isolation that requires no supervising and mutual monitoring, with the design concept of reducing the number of components, eliminating the occurrence of jamming, and shortening and reducing the fault transition time(12). The risk and safety engineering fields that are unique to aviation systems related to these new technologies become more important as we reach the stage of putting the systems into practical use.

7. Conclusion

In the six chapters above, we discussed the efforts for aircraft electrification by increasing the capacity of generators as the starting point. The distinctive approach of the MEAAP concept(18) can be found not only in the discussions about individual systems, but also in the revisit of the aircraft system as a whole. In other words, electricity is integrated into secondary power and managed, making it possible to optimize power demand and supply. Moreover, as heat generation increases in proportion to the increase in electric power, the cooling system to release such heat is integrated and optimized as exhaust heat management together with electric power management. Ensuring and improving safety is the top priority of aircrafts, and this paper has also looked at increasing the functionality of electrified systems and implementing multiple configurations. This paper is based on the technology policy of MEAAP.

IHI plays a role in MEAAP and aims to create new solutions to achieve aircraft electrification. Based on the pursuit of the highest efficiency and long-life design, which have been cultivated in the field of industrial machinery, we considered new requests that are unique to aircrafts, such as size and weight reductions, distribution, and high dynamic range, as goals that need to be achieved going forward. We have also created engineered systems (fully calculated systems) by working together with friendly rivalry and striving to achieve technological innovation in element levels and develop integration and optimization technologies. We firmly believe that engineers of the next generation will draw a contrail of an environmentally friendly electric aircraft and engine systems in the future.

— Acknowledgements —

Nabtesco Corporation, Sumitomo Precision Products Co., Ltd., SHIMADZU CORPORATION, SINFONIA TECHNOLOGY CO., LTD. and IHI started the study group on More Electric Architecture for Aircraft and Propulsion (MEAAP) in the early summer of 2012. We have continued research activities

and held approximately 40 meetings in five years. We are presenting this technical report on our research activities as part of the intermediate result.

As is usually the case with composite materials, there is an active push for aircraft electrification now. We, the MEAAP, formed this study group with the aim of promoting technology development by combining the skills of the companies involved and raising our ability and position in the world ahead of other countries in preparation for the next 10 to 20 years. We acquire all kinds of knowledge from around the world, such as airlines and universities, and will continue to present ourselves going forward. We would like to express our sincere thanks to those who have cooperated in our research.

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