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HIGH-SPEED COMPOUND HELICOPTER RESEARCH AT JAXA

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Abstract

An overview of the research on a high-speed compound helicopter carried out in JAXA is presented. JAXA proposed a distinctive configuration of a compound helicopter in 2014. The main rotor is combined with a fixed-wing to generate lift. A couple of motor-driven propellers installed on the fixed-wing tips with differential thrusts cancel out the torque caused by the main rotor. An engine-directly-driven propeller installed at the tail of the fuselage provides the main propulsion required to achieve a maximum flight speed up to 500 km/h. Major technology issues to realize the research target of “double the speed, same fuel mileage” are narrowed down to three topics: 1) the efficient rotor blade design in high-speed flight without sacrificing the hovering performance; 2) reduction of the drag caused by the rotor/wing aerodynamic interaction; and 3) the interaction between the main rotor and the propeller. We also investigate low-drag fuselage design including the fairing of the rotor-hub and cowling of the main rotor drive shaft.

Keywords: Compound helicopter, Optimal rotor, Rotor/wing interaction, Single-rotor lift-offset.

1. Introduction

We widely use conventional helicopters configured with a single main rotor and a tail rotor. However, the shock-wave build-up on the rotor advancing side and stall occurrence on the retreating side limit this type of helicopter’s possible maximum flight speed.

The compound helicopters retain the main rotors and add propellers to generate the required propulsion for high-speed flight. Two types of compound helicopters are mainly under development now. One utilizes coaxial rotors to generate the required lift represented by Sikorsky X2 [1]. During high-speed forward flight, lift offset, also called the advancing blade concept (ABC), improves the rotor aerodynamic performance. The other compound helicopter adds a wing to supplement the lift to a single main rotor during the forward flight, represented by Airbus Helicopters X3 [2]. Both demonstrated maximum flight speeds of more than 250 kts, nearly comparable to the tilt-rotor aircraft Osprey V22. The coaxial rotor-type compounds can be compact and efficient in hover. The concerns are the mechanically complicated rotor hub mechanism, vibration, and noise from the interactions between the rotors during flight.

On the other hand, the single main rotor type requires a fixed-wing to unload the main rotor during high-speed flight where the rotor advance ratio may exceed 0.6. Airbus Helicopters utilize a set of propellers installed on the wingtips to generate anti-torque and thrust simultaneously [3]. Technical issues with this type of compound helicopter are wing download and extra-required power to generate anti-torque, especially during hovering.

The authors proposed a new concept of a compound helicopter in 2014 [4]. Basic ideas are utilizing a couple of electrically driven propellers on the wingtips with differential thrusts between them just for anti-torque of the main rotor. An aft-mounted propeller driven by turbo-shaft engines provides the thrust required for fast flight. Since then, we have performed conceptual studies utilizing small-scale flyable models [5] and numerical simulations of the complex flow at high advance ratios [6], and interactions between the main rotor and the fixed-wing [7-9]. In addition, lift offset technology has been applied to the single-rotor type compound helicopter to improve aircraft performance [10]. Optimal design of the main rotor for high advance ratio flight is also underway [11-13]. We also investigate the interaction between the main rotor and the propellers [14, 15] and low drag fuselage design [16, 17].

In this report, we introduce the progress of research in JAXA on the key technologies related to the single rotor-type compound helicopter.

2. A Concept of Compound Helicopter Proposed by JAXA

The authors [5] propose a compound helicopter configuration for emergency medical service (EMS) application. As shown in Fig. 1, we design a 4-ton class rotorcraft to carry two crews with a doctor, a nurse, a patient, an accompanying person, and 50 kg of medical devices. The design target is to increase the maximum flight to approximately 500 km/h, nearly twice the conventional helicopter. This high-speed EMS helicopter can reach a radius of approximately 100 km within 15 minutes from the base hospital. As for the efficiency and cost of this rotorcraft, “double speed, same fuel mileage” was set as the research target.

There are several important technical issues to be solved to realize an efficient rotorcraft of such high speed, as shown in Fig. 2: firstly, an optimal rotor design suitable for high advance ratio flight is desired; secondly, based on the understanding of the rotor/wing interaction and the best rotor/wing lift-share, single-rotor lift-offset; thirdly, optimal propeller designs considering the interaction with the main rotor and the fuselage for the three propellers are studied. Finally, a low-drag fuselage design, which contains the landing gear retraction, hub faring, and mast cowling is also required.

Figure 1 – A conceptual design of a high-speed compound helicopter.

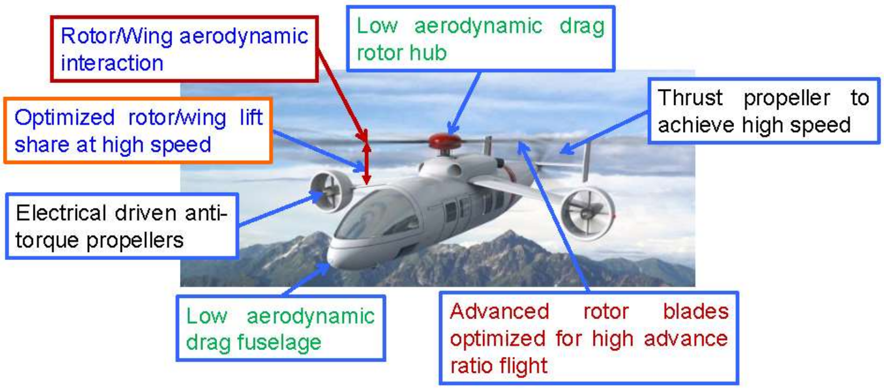

Figure 2 – Key technology issues to realize an efficient high-speed compound helicopter.

3. Optimal Rotor Design for High Advance Ratio Flight

The main rotors for the conventional helicopters are designed to fly in a range of advance ratio (ratio between the flight speed and rotor tip speed) less than 0.4 as the maximum. Considering the air compressibility barrier at the target maximum speed of the proposed compound helicopter, the rotor rotating speed could be decreased to approximately 75% of the rotor speed in hover, leading to a rotor advance ratio to be as high as 0.85. A large area of reversed flow region exists on the retreating side of the rotor. Furthermore, the rotor will rotate mainly in the horizontal plane, contrary to the conventional helicopter, where the rotor plane tilts forward together with the flight speed increase.

Therefore, it is very natural to believe there will be an optimal rotor blade design that could be quite different from those used on conventional helicopters.

Based on a patented design concept filed by the authors, three candidates of the optimal rotor blade shapes were picked-up from the Pareto front of the two objectives optimizations, as shown in Fig. 3 [11]. The figure of merit (FM) is evaluated at the gross weight same as the UH-60A during hovering flight. The effective lift-drag ratio (L/De) is evaluated at a rotor thrust of 30% of the gross weight assuming the fixed-wing will take 70% of the required lift at a cruising flight speed of 420 km/h. The rotor rotating speed is reduced to 75% of that in hover so that the rotor advance ratio, μ, is 0.7. The Optimal baseline shape has no blade tip swept, and the pre-twist angle and chord length distributions are shared with the Forward and Backward swept shapes. The Forward swept shape shows the best FM and L/De simultaneously. However, from the aeroelasticity stability consideration, the Backward swept shape with moderate performance is also retained for further evaluations.

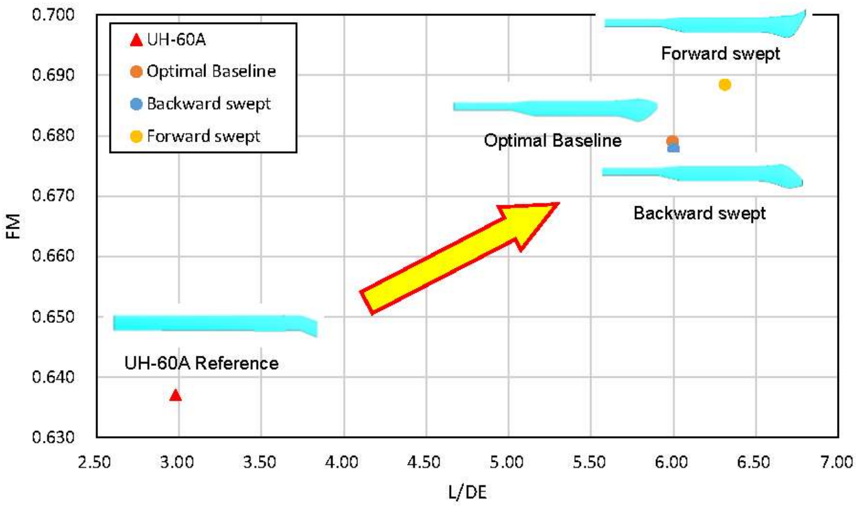

Figure 3 – Optimal rotor blade design for flight at μ=0.7.

The mechanism of superior forward flight performance in Forward swept shape is discussed based on CFD analysis [12]. As shown in Fig. 4, rotor blades in high-speed forward flight are affected by their own wake shadow, and the lift generated at the aft side of the rotor tends to be reduced. As a result, it causes a moment imbalance between front and aft, and a positive lateral cyclic pitch angle controls the rotor blades to compensate for this imbalance. Figure 5 compares the magnitude of the lateral cyclic pitch for various blade shapes, showing that the amount of control is minimal for the Forward swept shape.

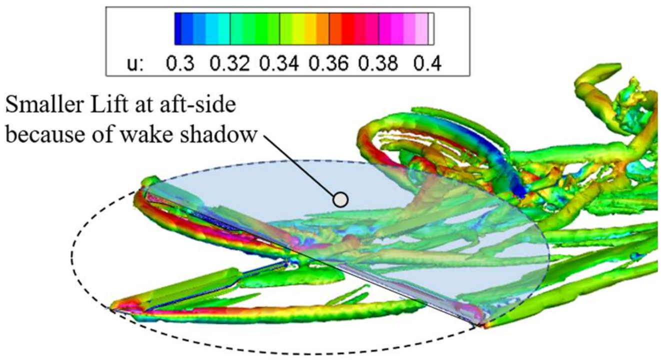

Figure 4 – Illustration of the relationship between wake shadow and front/aft moment balance

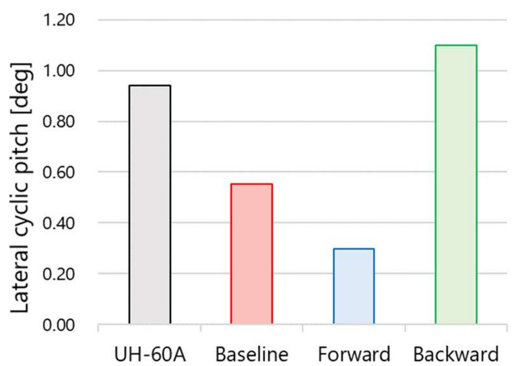

Figure 5 – Lateral cyclic pitch angles of each blade

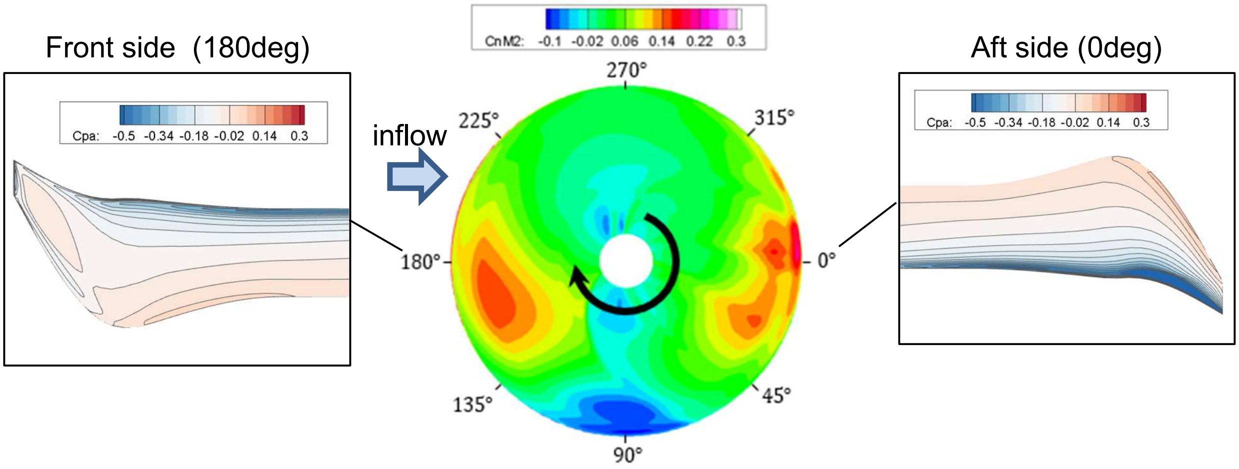

Figure 6 - Normalized lift distribution on the rotor disk with pressure distribution at front/aft positions (Forward swept blade)

The magnitude of lateral cyclic pitch angle is reduced in Forward swept shape can be explained by the pressure and lift distributions around the blade tip at the front/aft positions of the rotor. Figure 6 shows the lift distribution on the rotor disk and the pressure distribution around the blade tip at azimuth angles of 0 (aft) and 180°(front). The negative pressure peak around the tip is more pronounced on the aft side of the rotor, which makes it easier to generate lift on the aft side, where lift tends to be insufficient. This is a phenomenon peculiar to the addition of forward sweep angles to the blade and has been found to be beneficial in maintaining moment balance during forward flight, contributing to improved forward flight performance.

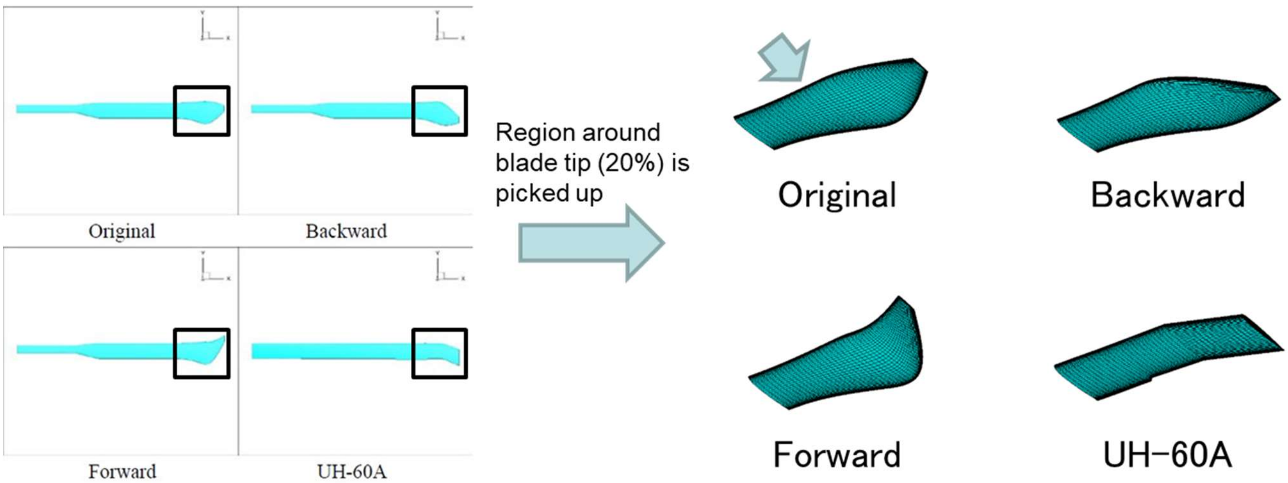

Figure 7 – Blade tip portion models [13].

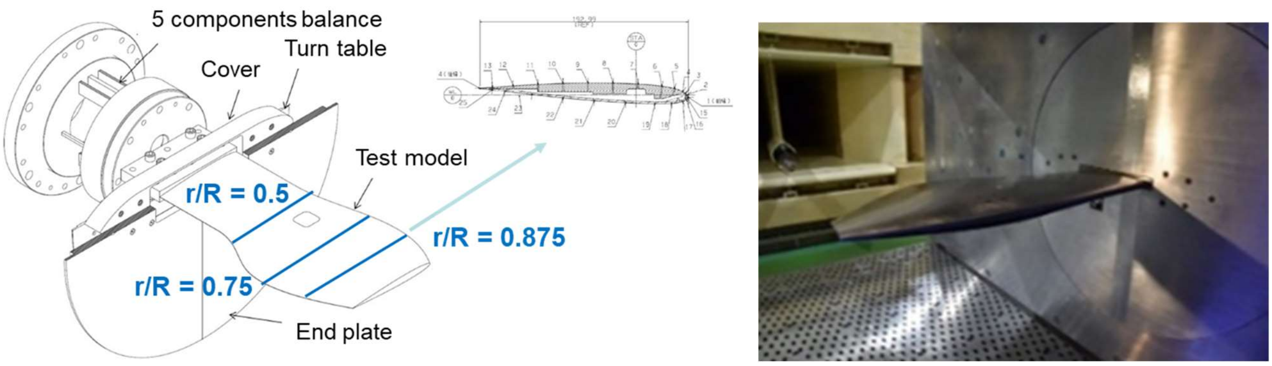

Figure 8 – Transonic wind-tunnel testing of the blade tip portions [13].

The three-blade tip portions of the optimal rotor candidates were tested in a transonic wind tunnel with the reference blade of UH-60A, as shown in Figs. 7 and 8. Details of the wind tunnel testing of the blade tips can be found in Ref. [13]. Excellent aerodynamic performance of the tip portions was confirmed. Verification of the rotor performance through wind tunnel and flight tests will be carried out using the scaled-down model rotors soon.

4. Rotor/Wing Interaction and Single-Rotor Lift-Offset

A typical flow field is shown in Fig. 9 for a compound helicopter in forward flight at an advance ratio of 0.7. However, the wake from the main rotor does not directly impact the fuselage and the wing. Instead, the aerodynamic interaction between the main rotor and the wing influences the aerodynamic performance of both the main rotor and the wing, similar to the bi-plane fixed wings.

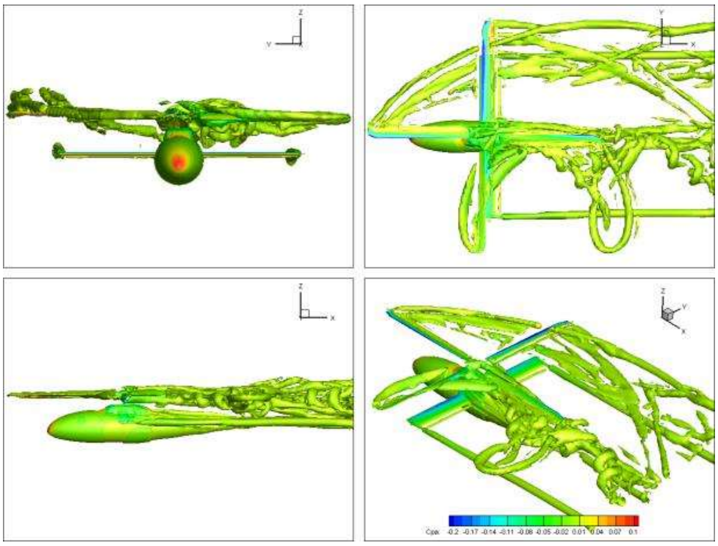

Figure 9 – Visualization of the flow field around the main rotor and a winged fuselage [9].

Large area flaps are installed on both sides of the wing [6]. By deflecting the flaps full down during hovering flight, the download on the wing caused by the main rotor downwash can be significantly eliminated. During forward flight, the flap on the rotor advancing side is turned up to reduce the wing lift, and the flap on the rotor retreating side is turned down to increase the wing lift so that a rolling moment is created. As a result, the single rotor on the advancing side can produce more lift to balance this rolling moment, working in a lift-offset state like the coaxial rotor lift-offset. The lift offset caused by the differential flaps depends on the rotor design, as shown in Fig. 10, and the resultant system lift-drag ratio is improved. As high as 11 of an effective lift-drag ratio can be achieved [10].

The lift distributions on the wing when the flap angles are zero for the two rotor types are shown in Fig. 11. Due to the aerodynamic interaction with the main rotor, the wing's lift on the advancing side is reduced more than that on the retreating side. As a result, the wing performance is degraded. However, with the application of the optimal rotor, the reduction of the lift of the wing is much lighter. As shown in Fig. 12, the normal force on the rotor disc for the optimal rotor is mainly generated on the fore and aft portions. Therefore, the normal force of the optimal rotor above the wing is small, which causes less interaction with the wing.

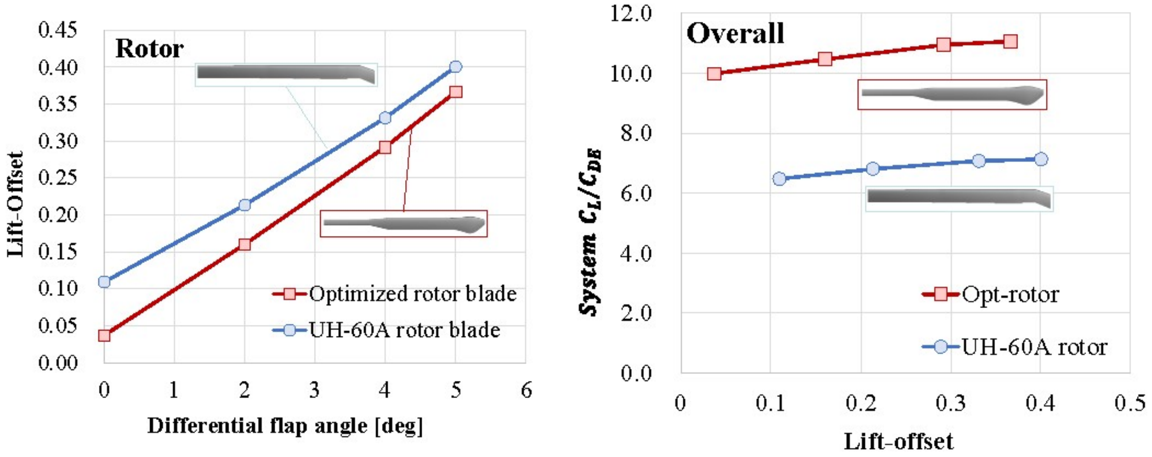

Figure 10 – Single-rotor lift-offset vs differential flap angle and improvement of system lift-drag ratio [10].

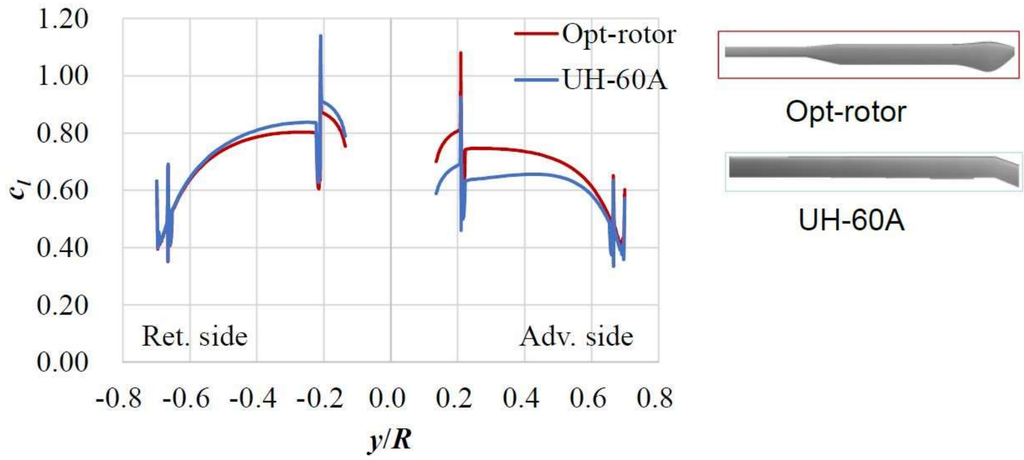

Figure 11 – Lift distributions on the wing for the optimal and UH-60A rotors [10].

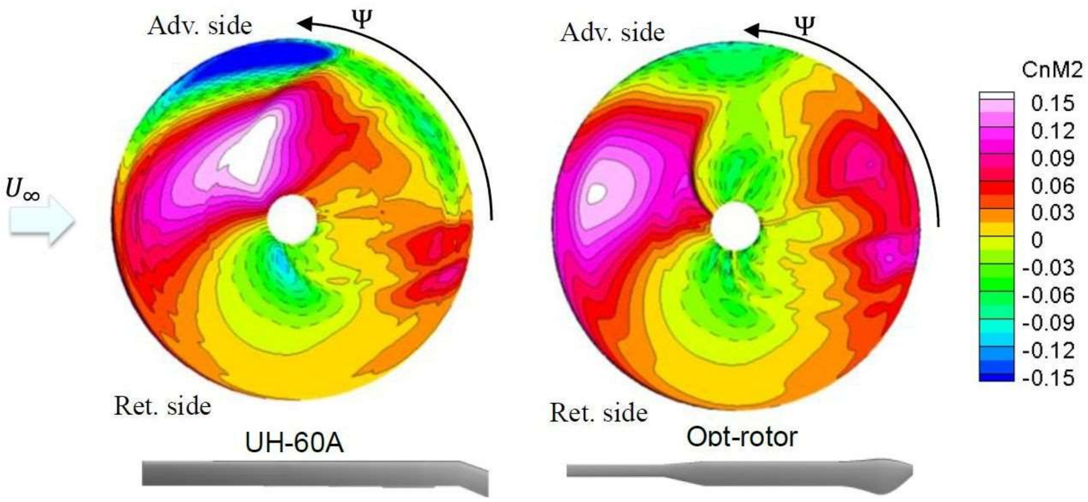

Figure 12 – Normal loading (CnM2) distribution on the rotor discs at $\mu = 0.7$ [10].

5. Rotor/Propeller Interaction

Based on the model compound helicopter, as shown in Fig. 13, the influence of the main rotor on the propellers is also studied [14, 15].

During hovering flight, the downwash from the main rotor is shown in Fig. 14. The side propellers are immersed in an unevenly distributed downwash caused by the main rotor. It changes the inflow condition of side propellers. The flow field around the side propeller is compared with the isolated flow field in Fig. 15. Focusing on the flow direction of the propeller wake, it can be seen that it is advected with the downwash of the main rotor. The downwash adds to the blade's rotational speed, thus increasing the dynamic pressure acting on the blade. Therefore, it tends to increase the thrust that can be generated. As a result, the figure of merit of the side propeller is improved, as shown in Fig. 16.

Figure 13 – Model compound helicopter with main rotor and side propellers.

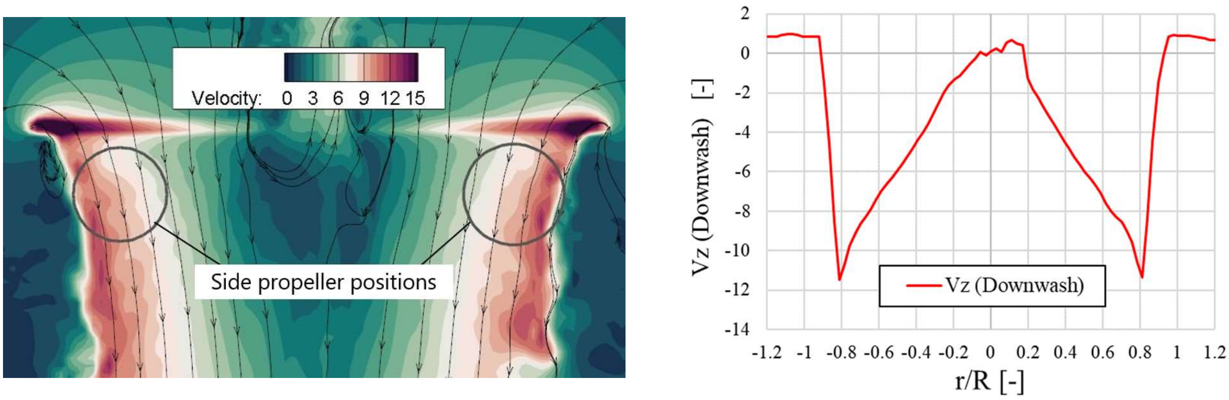

Figure 14 – Downwash from the main rotor at the position of the side rotor in hover [14].

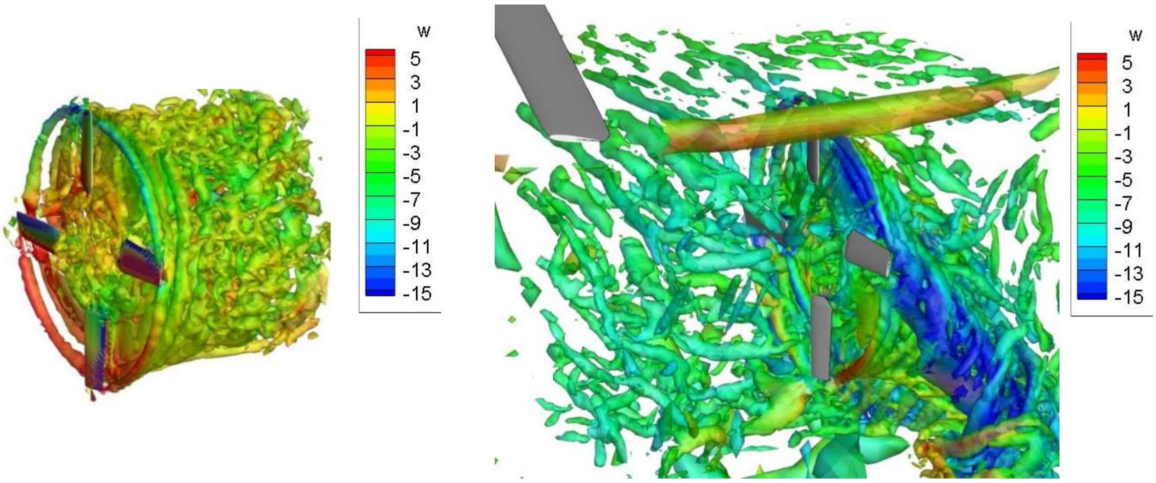

Figure 15 – Flow field around an isolated side propeller (left) and a side propeller with the main rotor (right).

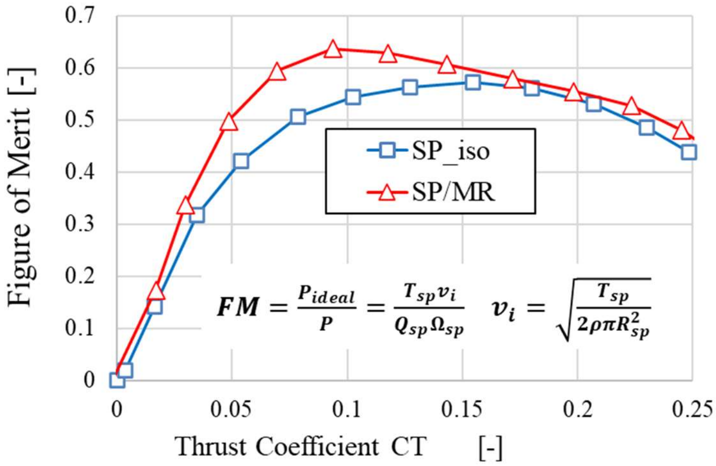

Figure 16 – Thrust and figure of merit of the side propeller [14].
(SP_iso : isolated side propeller case SP/MR : main rotor – side propeller interaction case)

6. Low-Drag Fuselage Design

Reducing airframe drag is of dominant importance for aircraft flying at high-speed. As shown in Fig. 17, the conceptually designed fuselage is of a streamlined shape. The landing gear can be retracted during flight. The rotor hub is faired to reduce the drag associated with the hub, where the geometry tends to be complicated. The mast and control rods will also be cowled in the final design.

Drag coefficients of the airframe with various configurations without the main rotor and propellers are shown in Fig. 18 [16]. The lowest drag coefficient based on the wing area is 0.1217, corresponding to an equivalent front flat plate area of 6.5 ft^2. Figure 19 shows an approximately 40% reduction from the value of a “clean helicopter” [18] of 4-ton gross weight.

Figure 17 – Wind-tunnel testing of the fuselage of the compound helicopter model [16].

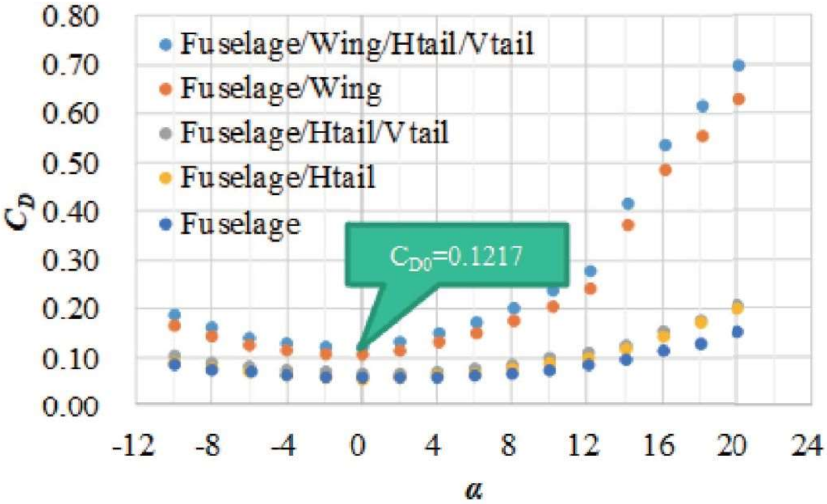

Figure 18 – Drag coefficient of the compound helicopter model with various configurations [16].

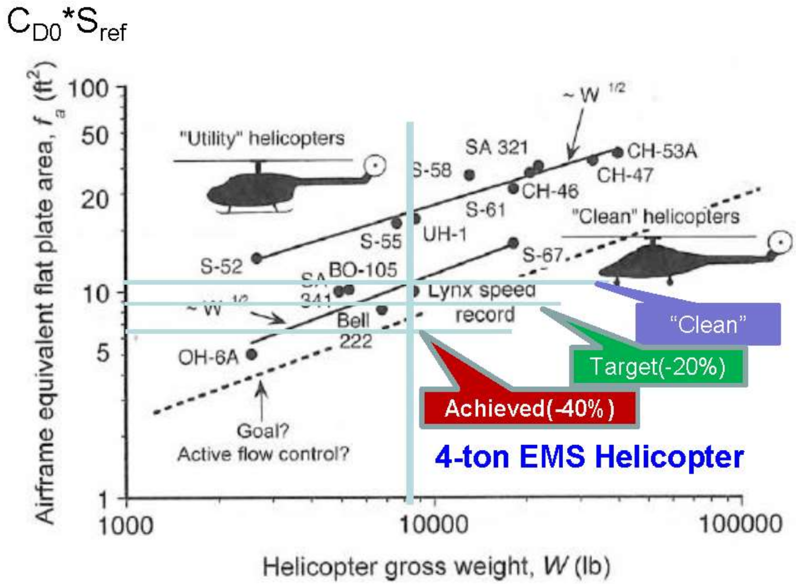

Figure 19 – Airframe equivalent flat plate area [16, 18].

7. High-Efficiency High-Speed Compound Helicopter Realization

By applying advanced technologies, the compound helicopter can be very efficient compared with conventional helicopters. Therefore, a conceptual study is performed to evaluate the effect of the above-mentioned technical issues, as shown in Fig. 20.

The fuel mileage is measured by the ratio between the required power (HP) and the flight speed (kt). An average of three helicopters (EC135, BK117D2, and AS365N3) which are often used as EMS helicopters, are taken as the reference. The typical flight speed of conventional helicopters is approximately 250 km/h. For a compound helicopter flying in a level attitude at 500 km/h with a “clean helicopter” airframe and a wing, approximately 1.64 times fuel mileage is predicted (JCH-0 in the figure). Please note that double the flight speed will lead to 4 times of fuel mileage for an airplane with the same drag coefficient. The benefit of the fixed-wing to generate 90% of the required lift contributes mainly to improve the mileage. By applying the low-drag airframe -40% from the “clean helicopter” (JCH-1), -1% saving of fuel mileage can be expected. By applying the optimal rotor where the rotor effective drag can be reduced by 50%, (JCH-2), -21% of fuel mileage can be achieved compared with the conventional helicopter. Applying the single-rotor lift offset to improve the combined rotor/wing performance by 12% (JCH-3), the fuel mileage can be further reduced up to -24% from the conventional helicopter.

Based on the above conceptual design study, it is shown that a compound helicopter can reach and surpass the research target "double the speed, same fuel mileage" by applying the advanced key technologies. Therefore, the potential to break the maximum flight speed barrier of the conventional helicopters and realize a very efficient aircraft with the single-rotor compound helicopter configuration is attractive and worth pursuing.

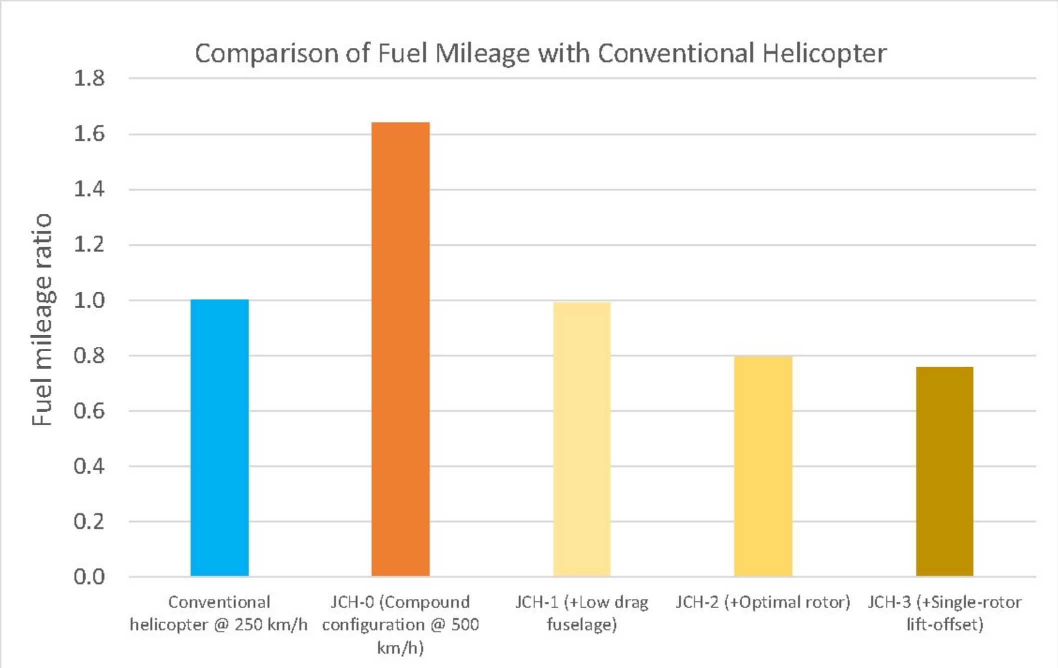

Figure 20 – Comparison of fuel mileage of compound helicopter with a conventional helicopter [19].

8. Summary

An overview of the research on a high-speed compound helicopter carried out in JAXA is presented. The configuration of the proposed compound helicopter is based on a single rotor with a fixed-wing to generate the lift. A couple of wing-tip propellers provide the anti-torque for the main rotor, and the main propulsion to achieve a target speed of 500 km/h is generated on an aft-mounted pusher propeller.

Progress of the major technical issues to realize the research target of "double the speed, same fuel mileage" is introduced.

1) Optimal rotor design for high advance ratio flight is conducted. Compared to the reference UH-60A rotor, the effective rotor lift/drag can be significantly improved.
2) Combined with the differential flaps on the wings, a single-rotor lift-offset state can be created, improving the aerodynamic performance of the rotor and the wing in high-speed flight.
3) Low-drag airframe can be designed by adopting a streamlined fuselage, retracting the landing gear in flight, and utilizing hub fairing and mast cowling.

By applying these advanced technologies to the single-rotor type compound helicopter, the research target of "double the speed, same fuel mileage" can be achieved or even surpassed.

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10. Copyright Statement

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