Numerical Study on Propeller Slipstream Effects on Objects at Low Reynolds Number

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Abstract

As a new form of a Mars exploration vehicle, research and development of a propeller-driven Mars airplane are progressing. Because the low atmospheric density on Mars causes the flow around the Mars airplane at low Reynolds numbers, the flow field around the Mars airplane differs from airplanes flying in the Earth's atmosphere. Besides, it is known that the propeller slipstream interacts with the fixed-wing and the fuselage and affects their aerodynamic characteristics. These interactions are important aerodynamic phenomena on the Earth airplane like eVTOL, because they arise at high Reynolds number. In the present study, we conduct numerical simulations and intend to clarify the unsteady effects of propeller slipstream on the fixed-wing and the fuselage at a wide range from low Reynolds number to high Reynolds number regions.

Reasons and benefits of using JAXA Supercomputer System

We used JSS3 to perform large-scale three-dimensional numerical simulations using the flow analysis solver "rFlow3D" , "FaSTAR" and "FaSTAR-Move" developed by JAXA. JSS3 can perform fast and multiple calculations.

Achievements of the Year

This work performed unsteady numerical simulations imitating the wind tunnel experiments conducted at Tohoku University. Comparing flow around the actual scale model of the Mars airplane (compressible flow around the propeller) and the subscale model used in the wind tunnel test(incompressible flow), we investigated compressible effects around the propeller on the aerodynamics characteristics of the fixed wing placed within the propeller slipstream. The Propeller advance ratio and the Reynolds number on both scales are the same value; $J = 0.8$ and $Re = 30{,}000$. The propeller rotation speed is $n = 4{,}500$, and the angle of attack was set to 4 deg. In this case, the blade tip Mach numbers are Mtip = 0.10 for the subscale model and Mtip = 0.52 for the actual scale model.

Figure 1 shows the instantaneous pressure coefficient and freestream-direction velocity contours around the propeller slipstream. It can be observed from the figures that the actual scale propeller emits weaker pressure waves than the subscale propeller, and the freestream-direction velocity in the propeller slipstream is less disturbed than the subscale model. This can be attributed to the stabilization of the separated shear layer over the blade owing to the compressibility effects. Figure 2 shows the time history of the lift coefficient of the fixed wing placed within the propeller slipstream during two propeller rotations. It is shown that the more disturbed flow behind the propeller in the subscale model leads to high-frequency vibration in the time history of the lift coefficient.

In this work, unsteady calculations simulating the level flight of the eVTOL at the high Reynolds number region were also carried out. Solving for the flow fields around the fuselage, fixed wing, and propellers, we investigated the aerodynamic interactions arising between them. The freestream velocity was M = 0.137 and the Reynolds number was Re = 3,100,000. The propeller rotation speed was n = 4,161.5 rpm and the blade setting angle was 55.7°.

Figure 3 shows the surface pressure distribution on the fuselage and fixed wing, which changes from moment to moment due to the propeller rotation. The pressure waves generated by the propeller rotation affect the surface pressure of not only the fixed wing but also the fuselage. This calculation quantitatively clarified the mechanism and the magnitude of this effect of aerodynamic interference caused by the propeller on the entire eVTOL, including the fuselage.

The oscillation of coaxial counter-rotating rotors in the low Reynolds number region as a function of the distance between the rotors was also investigated in this work. The calculations were performed for Re=11000 and for cases where the distance between the rotors was 10%, 20%, and 30% of the rotor diameter. As a result, oscillation was observed in the upper rotor due to the interference of the pressure field formed by the lower rotor, and in the lower rotor due to the wake generated by the upper rotor. The details of these oscillations were found to vary with the distance between the rotors.

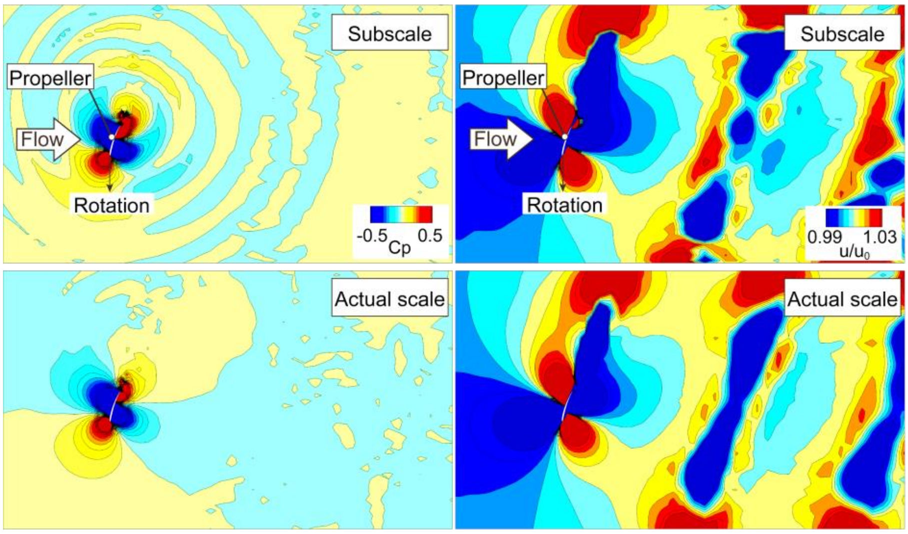

Fig. 1: Instantaneous pressure coefficient and freestream-direction vleocity contours around blade at cross-section of 63% span.

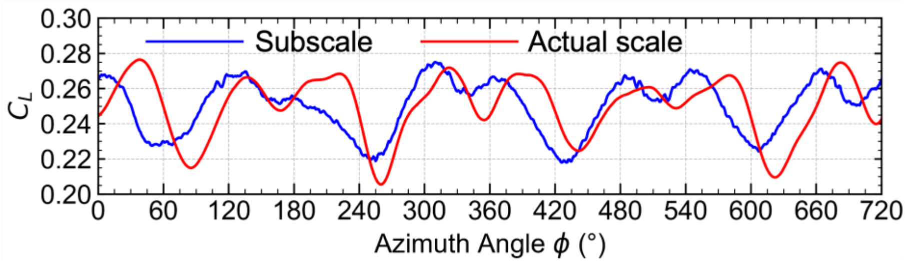

Fig. 2: Time histories of lift coefficient of fixed wing placed within propeller slipstream during two propeller rotations.

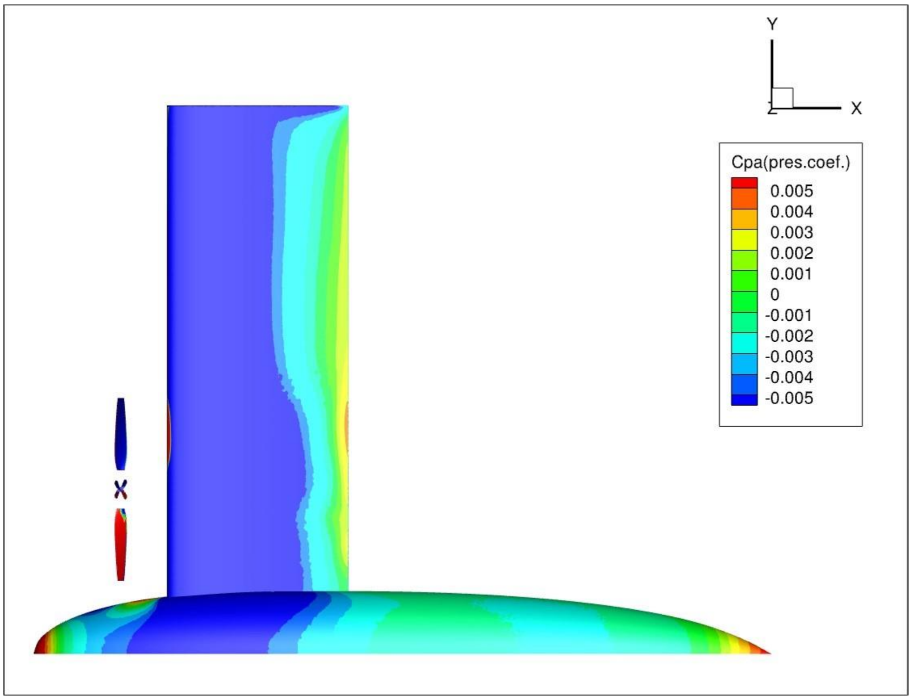

Fig. 3: Surface pressure coefficient distribution on fuselage and fixed wing.
(Video. Video is available on the web.)

Publications

- Peer-reviewed papers

Furusawa, Y., Kitamura, K., Ikami, T., Nagai, H., and Oyama, A., "Numerical Study on Aerodynamic Characteristics of Wing within Propeller Slipstream at Low-Reynolds-Number," Transactions of the Japan Society for Aeronautical and Space, Vol. 67, No. 1, 2024, pp. 12–22.

Furusawa, Y., Kitamura, K., Ikami, T., and Nagai, H., "Numerical Study on Unsteady Flow Field Structure over Wing within Propeller Slipstream at Low-Reynolds-Number," Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan. (accepted)

- Oral Presentations

Furusawa, Y., Kitamura, K., "Performance Comparison of Laminar-Turbulent Transition Models for Airfoil Flows at Low Reynolds Numbers (4,900 ≤ Re ≤ 50,000)", 54th Annual Meeting of Japan Society for Aeronautical and Space Science, 2023.

Furusawa, Y., Kitamura, K., Ikami, T., Okawa, M., and Nagai, H., "Propeller Scale Effect on Fixed Wing within Propeller Slipstream at Low Reynolds Number," 34th International Symposium on Space Technology and Science, 2023.

Furusawa, Y., Kitamura, K., Ikami, T., Okawa, M., and Nagai, H., "Compressibility Effects around Propeller on Propeller-Wing Aerodynamic Interaction for Mars Airplane," 20th International Conference on Flow Dynamics, 2023.

Suzuki, K. and Kitamura, K., "Numerical analysis of the effect of rotor position on eVTOL aircraft aerodynamics," 61th aircraft symposium, 2023.

Sakatsume, S. Kitamura, K. Nishimura, R. Ikami, T. Nagai, H., "Numerical Analysis on Low-Reynolds-Number Aerodynamic Oscillations of Coaxial Counter-Rotating Rotors," 61th aircraft symposium, 2023.

- Poster Presentations

Suzuki, K., Frusawa, Y., Mamashita, T. and Kitamura, K., "Grid Resolution Study on Numerical Analysis of Propeller-Wing Interaction," 34th International Symposium on Space Technology and Science, 2023

Usage of JSS

- **Computational Information**

Process Parallelization Methods	MPI
Thread Parallelization Methods	OpenMP
Number of Processes	36 - 1440
Elapsed Time per Case	720 Hour(s)

- **JSS3 Resources Used**

Fraction of Usage in Total Resources*1(%): 0.47

Details

Computational Resources		
System Name	CPU Resources Used (core x hours)	Fraction of Usage*2(%)
TOKI-SORA	7,537,874.43	0.34
TOKI-ST	1,213,778.14	1.31
TOKI-GP	0.00	0.00
TOKI-XM	0.00	0.00
TOKI-LM	106,714.94	8.13
TOKI-TST	5.55	0.00
TOKI-TGP	0.00	0.00
TOKI-TLM	0.00	0.00

File System Resources		
File System Name	Storage Assigned (GiB)	Fraction of Usage*2 (%)
/home	571.67	0.47
/data and /data2	66,343.33	0.41
/ssd	8,366.67	0.79

Archiver Resources		
Archiver Name	Storage Used (TiB)	Fraction of Usage*2 (%)
J-SPACE	9.83	0.04

*1: Fraction of Usage in Total Resources: Weighted average of three resource types (Computing, File System, and Archiver).

*2: Fraction of Usage：Percentage of usage relative to each resource used in one year.

- **ISV Software Licenses Used**

ISV Software Licenses Resources		
	ISV Software Licenses Used (Hours)	Fraction of Usage*2 (%)
ISV Software Licenses (Total)	3,432.19	1.55

*2: Fraction of Usage：Percentage of usage relative to each resource used in one year.