HPCI magazine
富岳百景
FUGAKU HYAKKEI
HPCI magazine vol.8

High-Fidelity Simulation of Airflow Ushering in a New Round of Innovation in Aircraft Design

Air and water constantly flow around us. Although we are not usually aware of it, technologies and products that make good use of these flows make our lives more convenient and prosperous. A typical example is airplanes. Recently, Prof. Kawai and his team succeeded in numerically simulating the airflow around an aircraft using a computer with overwhelmingly higher fidelity than ever before. This achievement was realized by combining the performance of the supercomputer Fugaku with the fundamental research that Prof. Kawai and his team have conducted over many years, and is expected to bring about a revolution in aircraft design.

Soshi Kawai
Professor, Department of Aerospace Engineering, Graduate School of Engineering, Tohoku University

"I Was Able to Realize Part of a Dream I Have Had Since My Graduate School Days."

Prof. Kawai discussed the history and current status of aircraft aerodynamic design as follows. "Computational fluid dynamics simulations have been used in aircraft aerodynamic design since the 1980s. Before that, until the Boeing 767, design relied on wind tunnel testing, which was costly and time-consuming. The introduction of numerical simulation has revolutionized aircraft design, but simulation can still only predict the flow around the aircraft with smooth geometry and under less-turbulent cruise conditions. Therefore, aircraft manufacturers expect the second round of innovation to occur when it becomes possible to simulate the flow around the entire aircraft (whole-aircraft simulation) during takeoff and landing, which involves complex geometries and highly turbulent flow.”

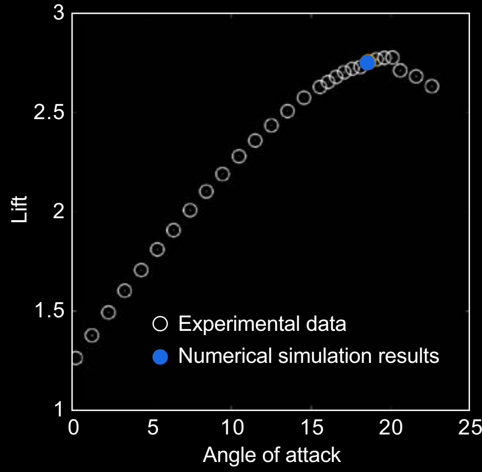
Since an aircraft raises its nose to obtain more lift during takeoff and landing, it is crucial to predict the relationship between the aircraft’s inclination (angle of attack) and lift in aircraft design. In particular, the maximum lift value significantly affects takeoff and landing performance, such as how much runway is required, and safety. Therefore, it is expected that a whole-aircraft simulation that can obtain lift values with high accuracy and can replace actual flight tests can be developed. However, this is not easy to achieve.

The flow follows the Navier-Stokes equations, which are solved numerically in Large Eddy Simulation (LES), where the space around the object is divided by a grid and the eddies (turbulence) with large energy are calculated directly on the grid. Prof. Kawai began researching LES in 2002, when he entered his doctoral program. In 2005, when he received his doctorate, he decided he wanted to use LES to analyze the flow around an entire aircraft. At the time, there was no one working on LES in the aerospace field in Japan. Since then, Prof. Kawai and his collaborators have conducted fundamental research and

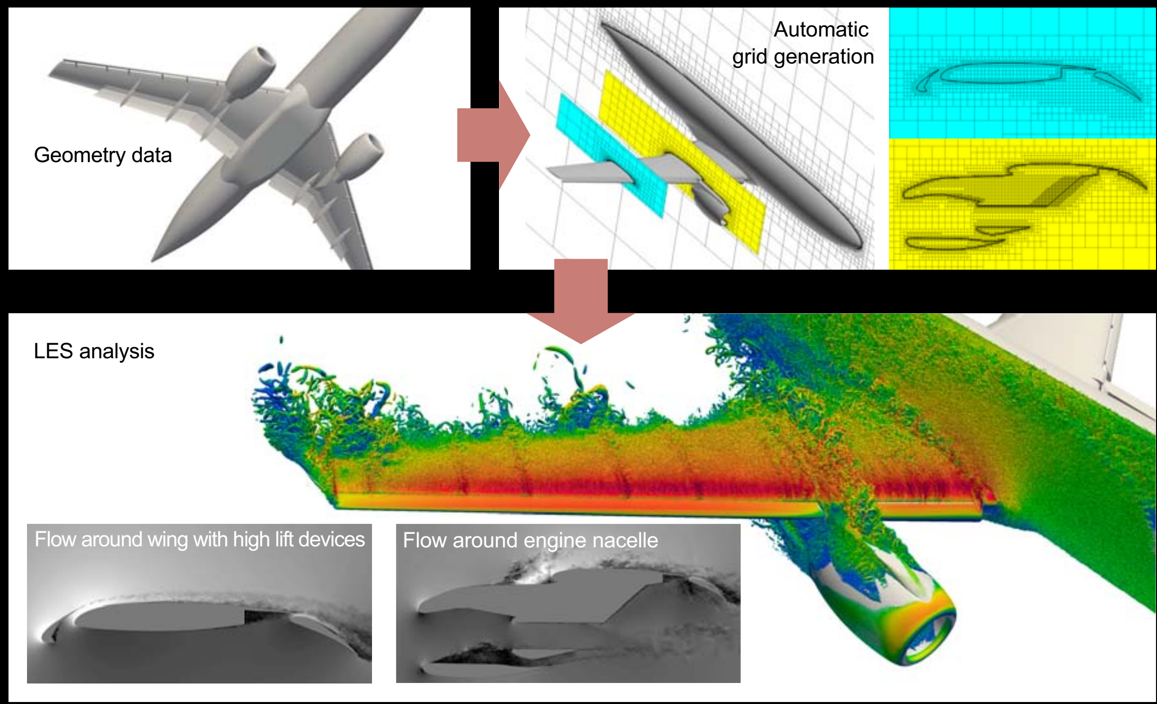
Fig. 1 Example of aircraft simulation using FFVHC-ACE

(a) JSM (JAXA Standard Model) was used as the aircraft geometry model, and the flow was calculated with approximately 12 billion grid points around the aircraft. The minimum grid spacing is 250 μm, and it took about two days to obtain the results of flow using 3,456 nodes of Fugaku for this calculation. The flow eddies (turbulence) around the wing and the longitudinal vortex from the engine nacelle are well reproduced. (b) The blue circle shows the lift near the maximum lift obtained from this simulation. It is in good agreement with the experimental data.

(b) Comparison of lift



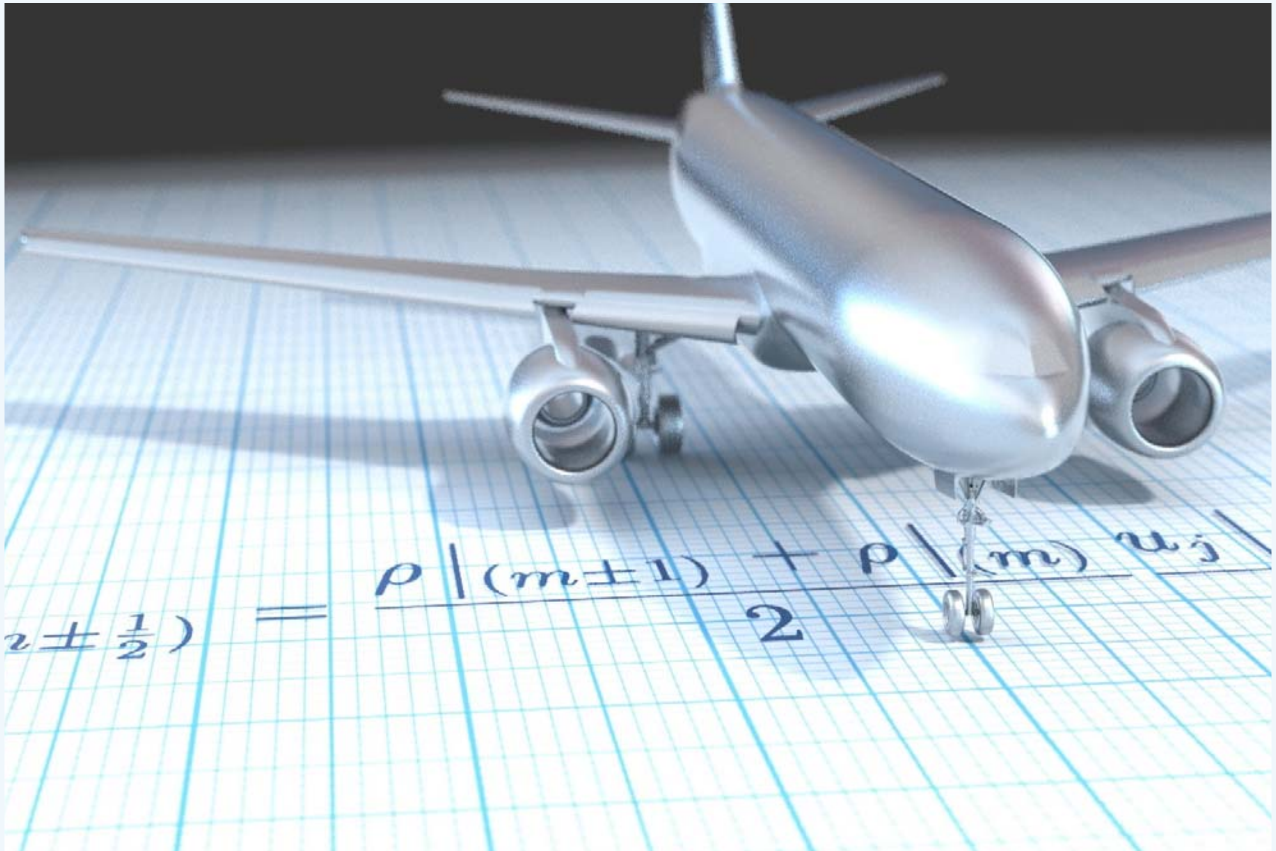
(a) Simulation processes



developed the “FFVHC-ACE” software, and recently succeeded in a high-fidelity (physically more accurate) simulation of the flow around an entire aircraft by using this software on Fugaku (Fig.1). Furthermore, the maximum lift obtained from these simulation results agreed well with experimental data. The results are beginning to meet the expectations of aircraft manufacturers.

Fundamental Research and Fugaku Made Difficult Simulations Possible

Why has it been so difficult to perform high-fidelity simulations of the flow around an aircraft? One reason is that the Reynolds number of the flow is very high, about 10 million. The Reynolds number is the ratio of the flow effect (inertial force) and viscous effect (viscous force) of the flow. When this number exceeds a certain value, eddies (turbulence) occur in the flow; the higher the value, the smaller the eddies. “LES is a method that simulates turbulent phenomena almost directly, so the prediction accuracy is high. However, to calculate small eddies, the grid size must be reduced, so the number of grid points required for the calculation becomes enormous, and the calculation cost jumps,” Prof. Kawai says.



In particular, the vortices are smaller near the walls of the aircraft, so Prof. Kawai has developed a physical model that accurately reflects the effects of small vortices near the walls (Fig. 2a). “Only very close to the surface of the aircraft, we replaced the LES calculations with calculations based on this model. This reduced the computation time by a factor of about 10,000. Without this modeling, we would not have been able to calculate for the entire aircraft even with all the nodes in Fugaku,” Prof. Kawai says, explaining the significance of the modeling.

Another reason why high-fidelity simulations are difficult is that the flow around the aircraft must be treated as a compressible flow. Computations of compressible flow are prone to instability, so existing software stabilizes the calculations with mathematical manipulations that provide artificial diffusion. However, this manipulation causes turbulence to decay in a way that is contrary to physics, and thus does not yield correct results.

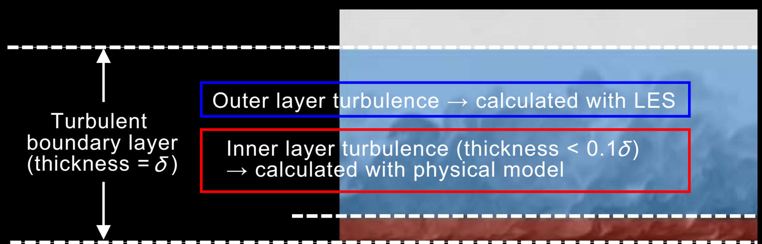
To counter this problem, Prof. Kawai and his colleagues established a calculation method named the KEEP (Kinetic-Energy and Entropy Preserving) scheme in their fundamental research. In compressible flow simulations, the flow is usually calculated under the condition that it satisfies the mass conservation law, momentum conservation law, and energy conservation law. In addition to them, the kinetic energy equation and entropy conservation law are satisfied when calculating with the KEEP scheme (Fig. 2b). The KEEP scheme allows researchers to conduct stable calculations without adding artificial diffusion and to obtain more physically correct results.

"In flow simulation, which requires large-scale calculations, the use of supercomputers has always been promoted, but Fugaku is very easy to use, and I think it is a good computer in terms of smoothly conducting large-scale computations. I believe that the results of this project have come out of a well-timed encounter between the fundamental research we have been conducting for many years and Fugaku, and the multiplication of the two," Prof. Kawai says.

Fig. 2 Two fundamental researches that enable high-fidelity simulations

(a) The thickness (δ) of the turbulent boundary layer that develops on the surface of the aircraft is about 3.5 mm at 10% of the position from the leading edge of the wing. An area less than one-tenth of this thickness (shown by the red shading) is modeled, and the rest is calculated using LES. This results in a speedup of about 10,000 times faster than when all of the boundary layer thickness is calculated with LES. (b) The usual compressible flow simulation is performed under the condition that the mass conservation law, momentum conservation law, and energy conservation law are satisfied, but in this calculation, a discretization method is devised to satisfy the kinetic energy equation and entropy conservation law. This enables stable and high-fidelity LES calculations.

(a) Wall-modeled LES



(b) KEEP (Kinetic Energy and Entropy Preserving) scheme

Governing equations for compressible flow (Euler equation without viscous term)

Mass conservation law

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0$$

Momentum conservation law

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} + \frac{\partial p}{\partial x_i} = 0$$

Energy conservation law

$$\frac{\partial E}{\partial t} + \frac{\partial E u_j}{\partial x_j} + \frac{\partial u_j p}{\partial x_j} = 0$$

Analytical

Discrete (existing methods)

Discrete (KEEP scheme)

Equations for secondary physical quantities

Kinetic energy equation

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho k u_j}{\partial x_j} + u_j \frac{\partial p}{\partial x_j} = 0$$

Entropy conservation law

$$\frac{\partial \rho s}{\partial t} + \frac{\partial \rho s u_j}{\partial x_j} = 0$$

Discretization is devised so that the equations for kinetic energy and entropy are also satisfied.

A Dream that Extends Beyond the Sky

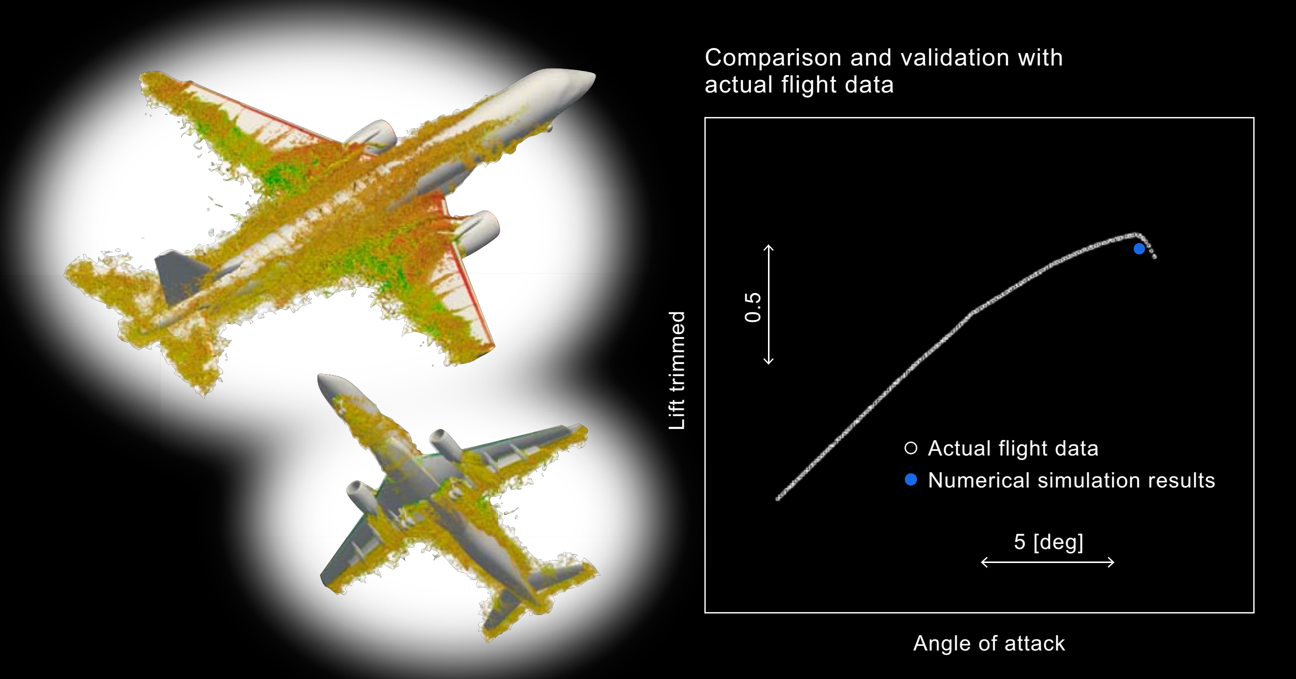
Prof. Kawai and his colleagues have applied FFVHC-ACE to several aircraft geometry models, and have confirmed that the maximum lift and other parameters agree well with experiments. “We are proud that FFVHC-ACE is the world’s most powerful compressible flow LES analysis software,” he says. “Moreover, industrial users only need to prepare geometry data to perform complex geometry LES calculations with high speed, ease, and high quality. In fact, the Mitsubishi Heavy Industries Group has successfully conducted a simulation using FFVHC-ACE and the geometry data of the SpaceJet and obtained good agreement with actual flight test data (Fig.3).”

However, Prof. Kawai is not satisfied with this achievement. “We will continue our research to predict not only takeoff and landing performance, but also high-speed flight limits, aerodynamic noise during the landing approach, and flutter phenomenon (severe vibration of the wings caused by flow), with the aim of using the FFVHC-ACE in aircraft design,” he says enthusiastically.

Prof. Kawai has a dream beyond this kind of success of the FFVHC-ACE. “Aerodynamic design of aircraft until now has relied heavily on experience, so it has been risky to develop an aircraft that looks different from past aircraft,” he says. “But that will become possible when various performance of an aircraft is accurately predicted through simulation. I would be happy if we can turn the ‘imagination’ of having an airplane of a desired geometry into an actual ‘creation’.” (Prof. Kawai used the Japanese word *souzou*, which means both “imagination” and “creation.”)

Fig. 3 Industrial applications of FFVHC-ACE

The Mitsubishi Heavy Industries Group (Mitsubishi Heavy Industries and Mitsubishi Aircraft) applied FFVHC-ACE to geometry data of the aircraft SpaceJet and conducted a simulation with Fugaku. Although Prof. Kawai was not directly involved in the calculations, only giving advice, the simulation was successful. The maximum lift was in good agreement with the actual flight test data, demonstrating that FFVHC-ACE is a high-fidelity compressible flow LES analysis software that can withstand use in academic research to industrial applications. Image courtesy of Mitsubishi Heavy Industries Group.



He also hopes to release FFVHC-ACE as a basic software that can be used for all kinds of compressible flow analysis, not restricted to aircraft, so that it can be used widely from academia to industry. The engineering fields involving compressible flow range from high-speed railroads and turbines for power generation to nozzles and diffusers, jet engines, and rockets. Since compressible flow simulations can directly determine the sound, which is the coarse and dense waves of air, simulations can also be used to find ways to reduce noise, which is a common problem in the industry.

The dream Prof. Kawai had 20 years ago is now becoming a reality through steady fundamental research and the advent of Fugaku. And now, it is about to expand beyond the framework of aircraft to the industrial world and bring about major innovations.

About the

Researcher

Prof. Kawai entered the Department of Aerospace Engineering at his university because of his childhood dream of becoming a pilot. Because of this, he enjoyed his student life so much that when he was assigned to a laboratory in his fourth year, he was astonished at the limitations of his knowledge. To become a responsible member of society, he studied hard and took a doctor’s course, where he was fascinated by the fun of research and became a researcher. His path was not smooth, however. For example, the place he was supposed to go as a postdoctoral researcher in the U.S. had to be changed due to the 9/11 terrorist attacks. “I have been blessed to meet many people, including a researcher I met at the new place and developed compressible flow calculation methods and a wall-modeled LES,” he says. Prof. Kawai loves spending time in nature and frequently visited national parks when he was studying abroad in the U.S. Now that he is in Sendai, he regrets that he does not have much time to spend in Tohoku's nature.

Associated Research Projects

“Leading Research on Innovative Aircraft Design Technologies to Replace Flight Test” (hp200137, hp210168, hp220160)
Principal Investigator: Soshi Kawai, Graduate School of Engineering, Tohoku University

HPCI magazine

富岳百景

FUGAKU HYAKKEI

HPCI magazine FUGAKU HYAKKEI vol.8

Registered Institution for Facilities Use Promotion / The Representative for HPCI Operation

Research Organization for Information Science and Technology

1-5-2, Minatojimaminami-machi, Chuo-ku, Kobe, Hyogo, 650-0047 JAPAN
Tel: +81-78-599-9511

HPCI Portal Site
https://www.hpci-office.jp/folders/english

HPCI PR site
https://fugaku100kei.jp/e/

Issued: August 2022