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High-precision Fluid Flow Simulations to Revolutionize Manufacturing

One of the crucial final steps in designing ships and cars is to produce a scale model or a prototype to evaluate real-world performance. These tests often require large facilities to reproduce the environments in which the vessel or vehicle will actually be used. If those tests could instead be carried out by computer simulations, it could make the design process much faster and less expensive. At present, however, both of the simulation software and the processing speed of even supercomputers are not enough to run such simulations with the required accuracy. As the principal investigator on a project under the “Program for Promoting Research on the Supercomputer Fugaku”,*1 Chisachi Kato intends to overcome these limitations. He has achieved simulations that could alter the performance testing conventionally done in ship design, and that can run within a feasible time during the design process.

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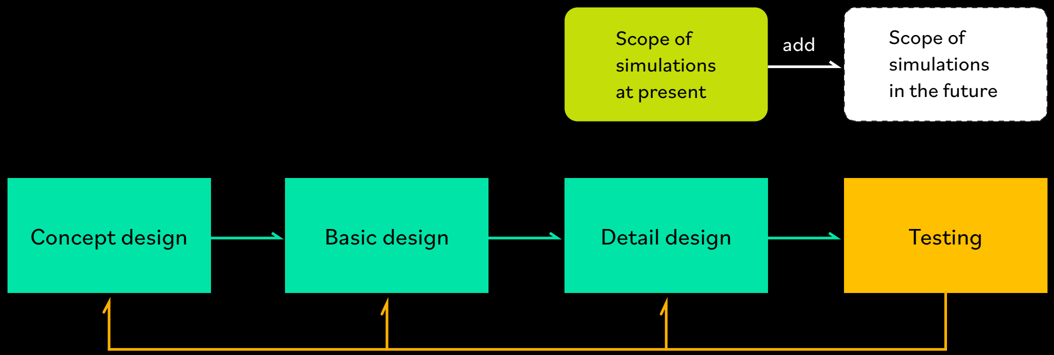
The Simulations Needed for Ship Design

Manufacturing vehicles or watercraft begins with a “concept design” that determines the basic shape, functions, and so forth of the product to be made. This is followed by a “basic design” that lays out the basic specifications of the product, a “detail design” that refines the detailed specifications, and finally performance tests using ship models or prototypes (Fig.1). Explaining the significance of his team's performance test simulations, Kato says, “a large ship model is built and tested in a big long ‘towing tank’ filled with water. The testing for a single ship design costs about 10 to 20 million yen and takes about a week. Our goal is to replace this real-world testing with computer simulations. If we can run simulations instead of the towing-tank tests, we can reduce the costs because we won't need to build a model ship to test. And if we find a performance problem, we can immediately modify the hull design to address it, which also saves time."

There are two main performance tests for ships: resistance testing and self-propulsion testing. In the resistance tests, a model ship is towed, without the propeller installed, to ascertain what resistance the hull encounters from the surrounding water. In the self-propulsion tests, the model is towed, with the propeller installed, to evaluate the interference effects between the hull and the propeller. A computational method known as "finite element analysis" is used to reproduce on computer the flow of water around the hull and propeller in simulations that aspire to completely replace the resistance and propulsion tests. In this method, the water around the hull is divided into a number of small segments called "elements", and the flow of water through these elements is computed according to the laws of physics.

Fig. 1 Expanding the use of simulations in manufacturing.

The design of a ship or automobile progresses through several stages: concept design, basic design, detail design, and finally, performance testing with models and prototypes. If a problem is detected in the performance tests, the designer must step back through the previous stages and start over, sometimes all the way back to the concept design stage. So far, simulations have mainly been used at the detail design stage. Replacing the prototyping and testing stages with simulations also could save time and money. Moreover, it could dramatically reduce the overall design time, since required changes detected at the performance testing stage could immediately be reflected in the design.



To replace the towing-tank tests, the hydrodynamic modeling must be highly precise and accurate. This means it is necessary to replicate swirling eddies*2 less than 1 millimeter in size near the hull exterior. With conventional computations, however, the number of elements around the hull was at most tens to hundreds of millions, not enough to reproduce such small eddies. Kato and his team ran simulations 1,000 times more detailed, using

*1 The "Research and Development of Innovative Fluid-dynamics Simulations for Aerodynamic/Hydrodynamic Performance Predictions by using Fugaku (Principal Investigator: Chisachi Kato)" research project consists of five research topics:
• Topic 1: "Realization of Numerical Towing Tanks and Improvements in Propulsion Efficiency with Energy Saving Devices"
• Topic 2: "Wall-Resolved Large Eddy Simulation of Internal Flow in a Multi-Stage Centrifugal Pump with Narrow Gaps"
• Topic 3: "Direct Analysis of Compressor Surge"
• Topic 4: "Prediction of Real-World Automotive Aerodynamic Performance"
• Topic 5: "Real-World Automotive Aerodynamic Sound Prediction"

*2 Includes a range of eddy sizes in temporally and spatially irregular flows.

from tens of billions to 100 billion elements, which could reproduce eddies less than 1 millimeter in size. Their simulations produced results that very closely matched the towing-tank test results (Fig.2).

Kato explains, “We had, in fact, done the same simulations before on the K computer. But they were so intensive that, even using around 25,000 of its compute nodes, the computations took about two days to complete. That's not fast enough for the actual design process. So, we've been doing research and development work on Fugaku with the goal of executing those computations in less than 1/30th the time.”

Fig. 2

The precision needed for computer simulations to replace towing-tank performance tests in ship design.

When testing a ship hull design, a scale model of the ship is towed in a long water tank, as shown in the photo at the top. The three graphs below compare waterflow velocities near the stern as obtained with: resistance testing in the water tank (top), conventional simulations (middle), and the new Fugaku simulations (bottom). The conventional simulations weren't able to reproduce the small turbulent eddies. But the new simulations use grids with 1,000 times as many grid points, allowing them to closely replicate the test results down to the small eddies. This is the level of precision that will be needed for simula-tions to replace the towing-tank performance tests.

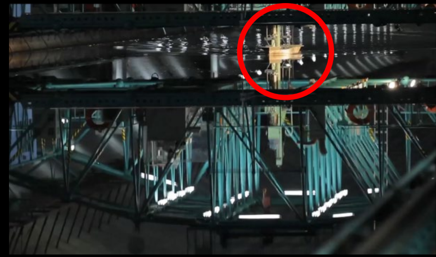


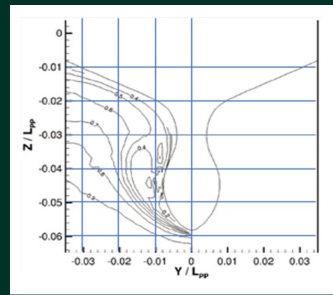
Image courtesy: Shipbuilding Research Center of Japan

Testing a model ship
(circled in red)

- Tank size: 400 x 18 m
- Water depth: 8 m
- Model length: 6 m
- Max. towing speed: 15 m/s (54 km/h)

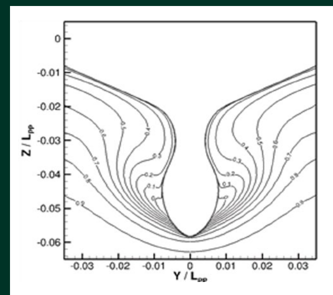
Flow velocities at ship rear
(Vertical cross-section)

Towing tank test results



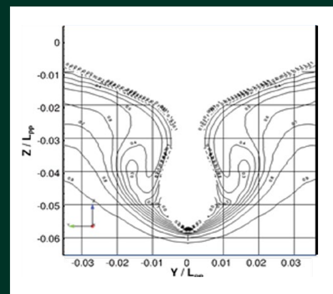
Conventional simulation results

Grid points (elements):
Tens to hundreds of millions



Simulation results in this study

Grid points (elements):
Tens of billions to 100 billion



Faster Data Transfer Rates Speeded Up Computations

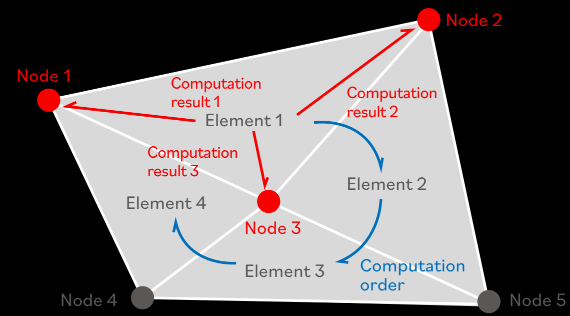
Kato and his team are developing a “flow solver” software based on the finite element method. It is called “FrontFlow/blue” (FFB). After completing his master's degree program in 1984, Kato joined a manufacturing company, where he wrote the software that served as a prototype for FFB. Since moving to a position in academia, he has been upgrading the FFB software, with the support of projects sponsored by MEXT, to achieve ever-better performance as supercomputers have grown more powerful.

Taking advantage of the distinctive design features of Fugaku, his team devised yet another way to reduce FFB's run time. They leveraged the faster rate at which data is transferred between the memory and the arithmetic logic unit in a CPU. FFB's computations require large amounts of data to be read from memory. The improved data transfer rate means faster execution.

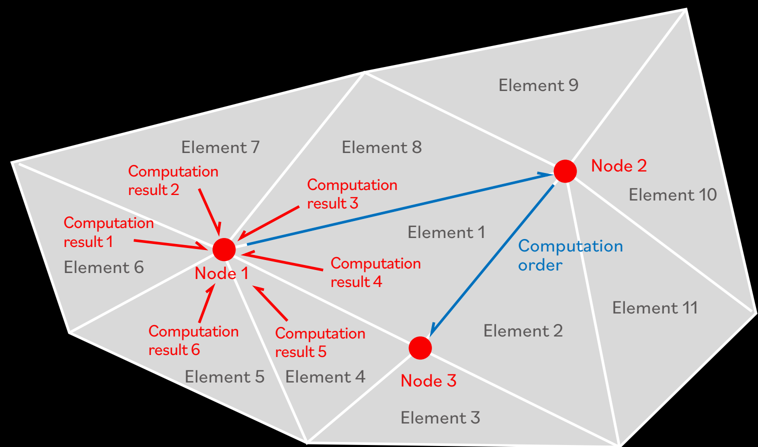
“One of our innovations was to arrange the data as carefully as possible when placing data into memory. This makes it possible to quickly retrieve the data to be used in computations. Another is that we have devised an algorithm with a modified finite element method (Fig. 3). Conventionally, element values are computed in order by element. But we decided to compute element values by node, in the order of the nodes that delineate the elements.”

Fig. 3 **A new algorithm utilizing Fugaku’s fast memory transfer.**

Conventional finite element algorithms compute in order by *element*. The value for Element 1 is computed first, then Element 2, and so on. FFB's new algorithm computes in order by *node*. All the elements sharing a common node are computed at once, and then those resulting values are used to update the value for that particular node, and so on. Changing the basic execution order of these computations takes full advantage of the performance offered by Fugaku's state-of-the-art CPU design.



Conventional finite element computation method

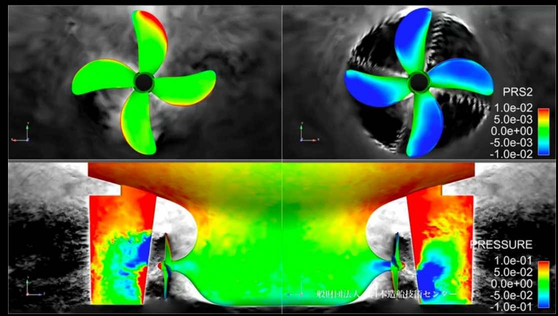


Computation method devised in this study

This increased the memory data transfer rate, nearing Fugaku's effective maximum memory bandwidth.[*3] The computations were executed 70 times faster on Fugaku than on the K computer. Computations that had taken around two days with the K computer were completed in less than an hour, a success far exceeding the team's goals.

*3 The actual maximum memory bandwidth performance according to benchmark software, rather than a theoretical memory bandwidth according to memory specifications.

Fig. 4 Simulations to evaluate waterflow interference effects near the propeller.



— Image courtesy: Shipbuilding Research Center of Japan.

The flow of water around the hull and the rotation of the propeller cause interference, which affects the propulsion performance of the ship. Self-propelled ship models are used in water tank tests to measure these interference effects. But these towing-tank tests are limited in how much detailed data they can provide. The new simulations, however, can provide much more detailed data, which is expected to lead to improved ship hull and propeller designs. Pressure is shown in color, and waterflow is shown in black and white.

Working with End Users to Make Simulations more Practical

Kato and his team have run simulations, with detail down to small eddies, on several ship hull designs. They check the water-flow around the hull during resistance testing, the interference effects between the hull and propeller during self-propelled testing (Fig.4), and the resistance caused by waves. The results have closely matched those of the towing-tank testing. The simulations are getting to a level where they can replace real-world tests.

Speaking about future plans, Kato says, “Our main goal is putting these simulations to actual use. So, we want to move forward with computations for various ship designs and other conditions to demonstrate that these simulations are usable in the design stages.”

But this is not limited to ships. The “Program for Promoting Research on the Supercomputer Fugaku” project that Kato oversees aims to make the use of supercomputer simulations feasible in the design of automobiles, pumps, compressors, and more. To facilitate industrial adoption, they have formed a consortium of 150 people from 54 organizations. They include the makers of ships, turbo-chargers, and hydraulic devices, as well as hardware and software vendors, who will work together to solve problems that manufacturers might encounter when implementing these computer models.

Kato has been working on software for fluid dynamics modeling since the dawn of supercomputers in Japan. The day when his efforts toward the practical use of simulations will bear fruit is just around the corner.

About the

Researcher

Chisachi Kato says as an elementary school student, he had a paper route to earn money to buy plastic models. At university, he majored in Mechanical Engineering and ran real-world experiments. But when he encountered computer-based simulations in his workplace after graduating, he became fascinated and has worked with simulations ever since. Having picked up organizational skills while working part-time as a mover and a party organizer, and with his attention to grammatical detail when preparing English manuscripts, computer simulation work seems to be his dream job. The research work doesn't seem to cause him stress. For fun, he plays golf with friends. He looks forward to playing again, once the COVID-19 crisis has ended.

Associated Research Projects

• “Research and Development of Innovative Fluid-dynamics Simulations for Aerodynamic/Hydrodynamic Performance Predictions by using Fugaku (Research and Development of a Turbomachinery Design Simulation System)” (hp200133)
Principal Investigator: Chisachi Kato, Institute of Industrial Science, The University of Tokyo
2020 ACM Gordon Bell Prize finalist for Research Findings

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