

Future Fluidics Analysis and an AI Surrogate Model for Manufacturing

— Can Super Simulation Enable Real-Time Wind-Structure Coupling Analysis? —

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1. INTRODUCTION

More than 120 of the world's countries, including Japan, have declared their intentions to "achieve carbon neutrality by 2050." Under these circumstances, large expectations are placed on expanded utilization of wind energy, and the construction of large-scale wind farms has proceeded. However, as the plant size and investment increase, requirements for prevention of accidents and outages and improvement of operating performance become more demanding. For this reason, "multiscale and multi-physics numerical analysis," in other words, "super simulation," which is performed to achieve greater accuracy in structural safety design and performance estimation, is necessary in the design stage. In the operation stage, it is also necessary to conduct system control so as to minimize fatigue damage accumulation on a continuous basis in order to ensure stable operation over the long term, and ideally, it will be necessary to consider conducting super simulations in real time. For this reason, demand for higher speed in numerical calculations in fluidics analysis is extremely strong.

In fluidics analysis, the method of numerically solving differential equations such as the Navier-Stokes equations has long been the orthodox approach. However, some fundamentally different idea seems to be needed in order to drastically increase computation speed.

As one possible solution, this paper introduces a "lattice gas method-AI surrogate model." This approach uses a "virtual particle model of a fluid analysis method called the 'lattice gas method'" as a substitute (surrogate model) for a "differential equation" that derives the fluid behavior. Fuzzy estimation becomes possible through the particle image in this model. In addition, a learning algorithm for measurement data can be obtained by making the model compatible with the computational structure of the neural network.

The development of this model is still in progress, and a simulation technique for verifying its effectiveness and method for comparison with experimental results have not been completed at this stage. Therefore, this paper mainly organizes the thinking that led to this concept, albeit in somewhat prosaic terms.

2. EXPANSION OF WIND ENERGY UTILIZATION AND FLUID ANALYSIS IN THE FUTURE

2.1 Need for High-Resolution Prediction in Fluidics for Wind Energy

A number of large-scale projects related to the use of various forms of renewable energy are underway with the aim of achieving carbon neutrality. Particularly for wind energy, huge wind farms are being built in rapid succession, and projects such as the development of wind-assisted operating ships (e.g., Wind Challenger¹⁾) and ocean energy harvesting vessels (e.g., Wind Hunter¹⁾) have been started with the aim of providing next-generation systems.

In such projects, the selection of a suitable construction site or operation site where the system can safely demonstrate high performance becomes increasingly important as the plant scale and investment become larger. Therefore, a preliminary evaluation using a numerical simulation with the highest possible accuracy is required. However, from the viewpoint of general theory, in order to predict the behavior of a fluid passing around a structure with high accuracy, it is necessary to resolve the images of all the fluid vortexes of various sizes that occur around the structure. Unless the image of a vortex that actually exists at a certain time can be resolved, the prediction of the behavior of the fluid around that point at that time will be erroneous. Therefore, "lattice points," where the flow velocity is to be calculated, should preferably be arranged at intervals as fine as the diameter of the smallest vortex. If the size of the smallest vortex is much smaller relative to the size of the structure, the number of lattice points arranged around the structure will be enormous. As will be described in section 3.1, in the case of a wind farm, the range of the length scale from the "size of the smallest vortex to be resolved" to the "size of the whole structure" would

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extend to several digits or more. Therefore, “**multiscale fluid analysis**” at a very high resolution is required.

2.2 Difficulty of Multiscale Fluid Analysis

With dimensional analysis in fluid dynamics, it is known that “generally, the value of the ratio between the ‘size (representative length) of a structure’ and the ‘diameter of the smallest vortex’ must be proportional to the $3/4^{\text{th}}$ power of the Reynolds number ²⁾ (Note: Reynolds number = representative flow velocity \times representative length / coefficient of kinematic viscosity).” The value of this ratio also serves as an indication of the number of lattice points to be arranged in the one-dimensional direction in cases where the resolution must extend to the smallest vortex. Therefore, when the behavior of a fluid is to be accurately predicted, the number of lattice points to be arranged will steeply increase in proportion to the product of the number of lattice points in the three-dimensional direction, and if the Reynolds number exceeds a certain size, it will be impossible to complete the numerical calculation within a practically acceptable time. In other words, as the Reynolds number becomes larger, it becomes more difficult to perform a multiscale fluid analysis in terms of calculation time.

2.3 High-Resolution Prediction Using Present Numerical Fluid Dynamics

This section lays out the general theory for achieving a high-resolution simulation in fluidics analysis for manufacturing from the author’s point of view.

As a result of the remarkable improvement in supercomputer performance, it has now become possible to complete the necessary time evolution calculation within a practical time, even for a lattice point arrangement with very high resolution. Having said that, there is always a highest number of lattice points at which the calculation can be completed within an acceptable time. First, therefore, when attempting a high-resolution simulation, the number of lattice points to be arranged should be as close to that number as possible. In fluid analysis on an experimental or prototyping scale, the Reynolds number is not particularly large, so resolution to a level that includes the smallest vortex might be possible with the fineness of that lattice point arrangement. In this case, the extra work of considering the fluid state of further details between the lattice points is unnecessary. In other words, a direct numerical simulation (DNS) for the fluid which does not require this work would be achievable, and it would be possible to obtain an accurate simulation result. In full-scale fluid analyses, however, the Reynolds number would be excessively large. Therefore, it is still difficult to perform a simulated calculation which is capable of resolving the image of the smallest vortex only with DNS, even with the most recent supercomputers. For this reason, the turbulence model approach is adopted, in which “interpolating estimation is performed by setting a certain assumption (model)” for any part finer than the interval between lattice points, after finding the physical quantities such as the flow velocity at each lattice point. Sufficient accuracy can be secured with this approach in some cases, although this depends on the purpose of the simulation. However, this model assumption lacks physical generality in many cases, and the resulting uncertainty may have an unacceptable effect on the simulation results.

3. SETTING A DREAM TARGET AND ATTEMPTING BACK-CASTING THINKING

3.1 Ideal Resolution Is a Width of 5 to 6 Digits per Dimension

Around the end of last year, The Denki (ENERGY & ELECTRICITY) Shimbun newspaper published an article entitled “On November 24, 2021, Siemens Gamesa Renewable Energy in Spain was awarded a contract for 69 windmills for Finland’s largest onshore wind farm.” According to that article, the windmill rotor diameter is approximately 170 m and the tower height is approximately 150 m. In this section, it is assumed that the resolution required for an aerodynamic calculation at each region of the windmill blade is estimated to be approximately 5 mm, which is larger than the actual smallest vortex (Kolmogorov scale). This is the result of considering factors such as the fact that the smallest scale of practical turbulence is assumed to be approximately five times the Kolmogorov scale ³⁾, and it is an assumption in a direction which makes the achievement of the target resolution easier. However, even in this case, the difference in the “length scale” in comparison with the blade length is a four-digit number.

As an additional problem, in a wind farm, the wake flow of a windmill is affected by the presence of a downstream windmill and the overlap with the wake flow of that windmill, resulting in a complex wake flow that also reaches windmills located further downstream. For highly accurate prediction of power generation, it is necessary to analyze the state of such wake flows for the entire wind farm, in addition to the wind prediction that considers the topography of the wind farm site. Therefore, the sparse and dense arrangement of lattice points must be adjusted while considering the size of the fluid vortices in the respective

parts of a vast spatial region extending from several km to 10 km in the horizontal direction and 500 m or more in the vertical direction. This means it is necessary to arrange a huge number of lattice points in the entire wind farm, particularly if a high-resolution lattice point arrangement with an interval of 5 mm near the rotors of all the windmills is required. In the horizontal direction, the number would be $5 \text{ km} \div 5 \text{ mm} = 10^6$. However, since a lattice point arrangement with super high resolution of approximately 5 mm intervals is not required for all lengths, arrangement of $10^{5\sim 6}$ lattice points per dimension would give an indication of the “dream target.”

This guideline is also surprisingly reasonable in other fields of fluidics analysis. For example, in a study of the air resistance of a running automobile, Tsubokura published findings indicating that if a numerical analysis (LES) in which the resolution near the boundary where the automobile comes into contact with the atmosphere is fined down to the order of 0.1 mm, the behavior can be predicted with an error of 1 to 2% from the value obtained in a wind-tunnel experiment using a full-scale automobile model⁴⁾. Similarly, in an investigation of the total resistance coefficient of a ship, Nishikawa found that a numerical analysis (DNS) of the state of a tank test of a towed model ship (approx. 5.5 m) at a resolution of approximately 0.05 mm with an arrangement of approximately 32 billion lattice points could predict the behavior of the ship with accuracy within 1%, which is the measurement error of the tank test⁵⁾.

Therefore, in quantitative terms, **“realizing high-resolution multiscale analysis in which $10^{5\sim 6}$ lattice points per dimension are arranged”** is considered to be an ambitious target in future fluidics analysis for manufacturing.

3.2 Requirements of Multi-Physics Hampering Target Achievement

In any of the three cases of a “wind farm,” a “wind-assisted operating ship,” and an “ocean energy harvesting vessel” mentioned in section 2.1, the fluid (atmosphere or seawater) interacts with an elastically deformable structure (e.g., windmill blade, ship sail). Particularly in wind farms, windmills are placed in an extremely complex wake flow, as described above, but in the analysis of the windmill structure, a strength analysis accompanying elastic deformation and a fatigue analysis for achieving stable operation over a long service life should be conducted as accurately as possible. In the cases of a “wind-assisted operating ship” and an “ocean energy harvesting vessel,” a gas phase (atmosphere) and a liquid phase (seawater) coexist in the fluid, while the structure tends to rock dynamically on the boundary between those two phases. To evaluate the soundness of the structure under a condition of continuing complex motion of this type, **“multi-physics coupled analysis”** is essential. In this type of analysis, different physical equations for the fluid and the structure are continually coupled in order to perform the calculation, and in this coupled analysis, the multi-physics calculation is incorporated into the time evolution calculation, while also maintaining the high-resolution arrangement required for the multiscale analysis. Since a substantial increase in calculation time is normally unavoidable under these constraints, achievement of the numerical target in the multiscale fluid analysis mentioned in section 3.1 becomes an even more challenging goal.

3.3 Real World Requirements Hampering Target Achievement

In the natural environment of the real world, unexpected sudden changes, exemplified by changes in wind conditions, are a frequent occurrence. Therefore, in the operation stage, it is important to prevent any anomaly resulting from a sudden change in wind conditions from developing into an accident, and to extend the life of the system by preventing excessive accumulation of fatigue damage even in such cases. For that purpose, feedback control which is capable of responding promptly to sudden changes in the external environment is necessary. Conducting this control with high accuracy requires a technology for **“real-time data assimilation (real-time measurement fusion simulation)”** that enables prompt reflection of on-site measurement information in simulations. Under normal circumstances, the time required for the data assimilation calculation will unavoidably lead to an increase in calculation time, depending on the selection of the method for reflecting the simulated calculation results in feedback control.

3.4 Dream of High-Speed Super Simulation

From the viewpoint of the technologies that constitute a supercomputer, the numerical target of multiscale fluid analysis described in section 3.1 is a task of achieving massively parallel super-fast data transmission between super-large memories. While this task is in itself very difficult, achieving this target while simultaneously satisfying the “requirements of multi-physics” described in section 3.2 and the “real-world requirements” described in section 3.3 would seem to be an “impossible dream.”

In a “super simulation” which combines multiscale fluid analysis with a coupled analysis of the interactions of the fluid and the structure, the orthodox approach is currently the method of proceeding with a time evolution calculation by calculating the behavior of the fluidic part by using a finite difference solution such as the Navier-Stokes equation and the structural part by

using the finite element method, and constantly exchanging information on the state quantities of the two. Since approaches of this type have in fact produced meaningful results ⁶⁾, it can be said that this as an extremely reasonable approach from the viewpoint of solidifying the foundations of the technology.

However, this paper pursues the dream of achieving “super simulation” in real time, and discusses the issue by back-casting thinking based on the multiscale numerical target described in section 3.1. The purpose of this effort is to discover the possibility of realizing this dream, even if only slightly. From this point of view, the first step is to explore a method for drastically reducing the burden on the computer when it performs a high-resolution multiscale analysis.

[Panoramic Perspective] Method for Converging from the Virtual World to Reality

The approaches for computer simulations used in “fluidics analysis for manufacturing” can be roughly summarized as follows.

In general, many phenomena in the real world interact with each other and also fluctuate on an extensive spatial and temporal scale. Therefore, when attempting to reproduce real behavior faithfully by a numerical simulation, a complex and elaborate simulation model that has both a “multi-physics nature” for coupling a larger number of physical phenomena and a “multiscale nature” for capturing fluctuations in a larger spatial and temporal range will be needed.

As one example, the author was formerly a member of a project team for developing a supercomputer called the “Earth Simulator (first-generation),” and at that time, one argument exemplifying the above-mentioned point can be summarized as follows: “One of the important phenomena in prediction of global warming is ‘general circulation of seawater on a global scale (oceanic general circulation).’ In a simulation of this behavior, a physical model that simulates the circulation of only seawater by solving an approximation equation based on the laws of physics serves as the core. However, in order to approach the real-world phenomena more closely, it is necessary to evolve the model into one which is coupled with ‘atmospheric general circulation’ so as to consider the driving force due to air on the sea surface and the changes in the sea surface height due to factors such as precipitation and evaporation. Moreover, if that model can be coupled with a model which is capable of calculating factors such as the ‘downward seawater flow due to icebergs’ and the ‘impact of changes in air composition due to the ecosystem on the atmosphere and seawater through greenhouse effect,’ it would be possible to simulate the real world more faithfully.”

This kind of approach, which is based on “**numerical solution of approximation equation and elaboration of the model,**” has long been the prime orthodox approach in numerical simulations (cf. Fig. 1). However, as the elaboration becomes more advanced, the complexity of the model calculation also increases, making it impossible to complete the computation within a practical time. In contrast to this, the second approach is to “**start from a more fundamental equation.**” For example, one such method is an attempt to simulate a phenomenon of fluidic scale by using molecular dynamics. Because the real world which is the focus of interest in this case is molecular groups at least of the order of Avogadro numbers (10^{24}), if calculations are accumulated from the molecular size world, the extent of the multiscale digits would exceed 8 digits per dimension. Even with today’s rapidly-advancing high-performance computers, the operation speed and storage capacity are still far short of the performance needed to complete this calculation within a practical time.

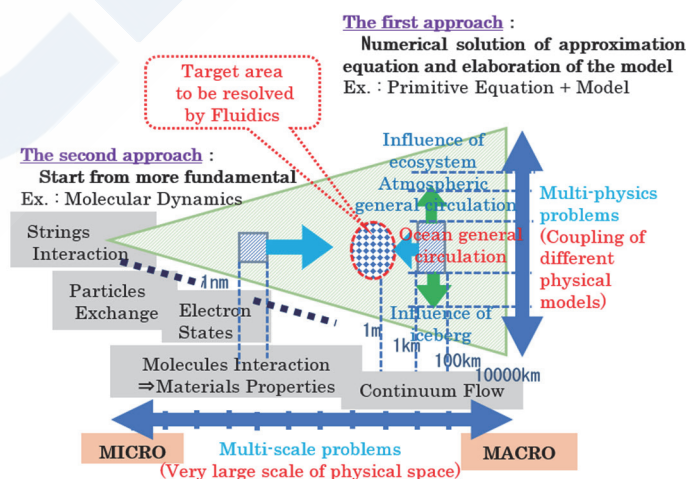


Fig. 1 Multiscale and multi-physics ⁷⁾

Under these circumstances, the third approach (cf. Fig. 2) is to “derive phenomena of the real world by imagining a virtual world with a scale one step finer than the spatial and temporal scales of the phenomenon to be analyzed, setting a simple rule that governs the temporal development of that world, solving this rule at high speed using a computer, and then averaging the behaviors of the obtained virtual world within an appropriate range of space and time.” Such an approach of “**converging from the virtual world to reality**” is capable of substantially shortening computational time and is clearly advantageous from the viewpoint of real-time simulation. Specific techniques of this type include the lattice gas method and the lattice Boltzmann method.

These approaches are characterized by the fact that the behavior of a continuous fluid is simulated by the “collective behavior of virtual particles of sub-macro scale.” Here, “sub-macro scale” means a scale one step finer than the temporal-spatial scale to be analyzed. This “sub-macro scale” is not intended to faithfully simulate the real world, and in fact, even when the real fluid is viewed at the sub-macro scale, it is still a “continuum,” and nothing resembling a “particle” is observed. In other words, this approach assumes a “virtual particle having a size of sub-macro scale” and considers the mechanism that controls its behavior, despite knowing that it is obviously different from reality. The determination of whether or not the “sub-macro particle model” is an appropriate “surrogate model” of a “real large molecule group that appears to be a continuum” is made according to whether or not the parameter can be adjusted to match the real behavior when the model is averaged in an appropriate temporal-spatial range.

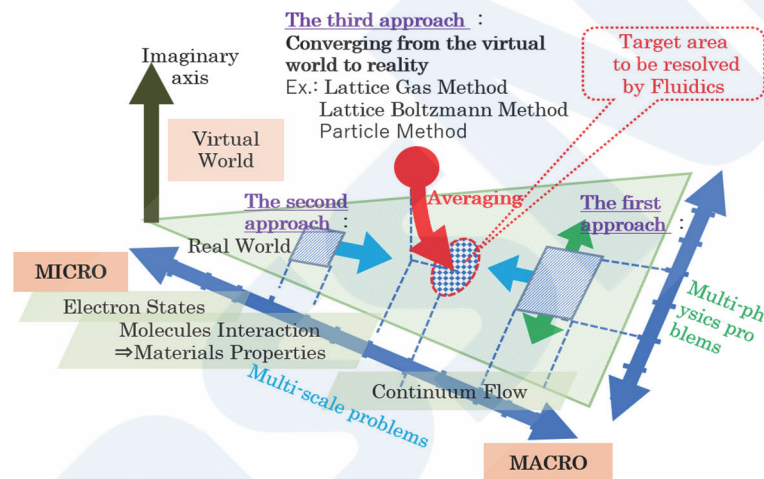


Fig. 2 Approach of “converging from the virtual world to reality”⁷⁾

It may be noted that there is also a powerful simulation approach called the “particle method”⁸⁾ which can be applied to various multi-physics simulations. The “virtual particle” in the particle method is a substitute for a fluid mass or the like on the macro scale, which is created in the form of a “particle model” with the same scale. While this eliminates the need to perform the averaging (coarse graining) operation, at the stage where humans examine the calculation result in order to understand the real physical behavior, it is thought that they do in fact mentally average the “movements of individual particles” in a certain temporal-spatial range and take a general overview of the collective behavior of the particles. For this reason, the author classifies the particle method in the category of approaches called “convergence from the virtual world to reality,” as in the case of the lattice gas method and the lattice Boltzmann method.

4. AIMING AT REALIZING MULTISCALE HIGH-SPEED CALCULATION (Proposal of a Simplified Model Eliminating All Real-Number Representations)

4.1 Operation with One Lattice Point and One Bit Width for Sparse and Dense Lattices

4.1.1 Selecting the “Lattice Gas Method” as the Basic Technique

Although the “lattice gas method,” “lattice Boltzmann method” and “particle method” are all used to calculate the behavior of a “virtual particle,” each approach has both merits and demerits from the viewpoint of calculation efficiency. This section focuses on the difference in “representation of physical quantities” which is handled when a time evolution calculation is

performed. In the particle method, there is no lattice that constrains the position of the virtual particle (meshless). This means the position of a virtual particle can take a free real value. In addition, the velocity of a virtual particle is also represented by a continuously changing real value. In the lattice Boltzmann method, the position of the virtual particle is constrained on a lattice point, and only a certain discretized finite number of values can be taken for its velocity. However, the distribution of the probabilities that virtual particles will take the respective velocities is represented by a real number, and this is used in the time evolution calculation. In the lattice gas method, as in the lattice Boltzmann method, the position of the virtual particle is constrained on a lattice point, and only a certain discretized finite number of values can be taken for its velocity. The difference between these methods is that the lattice gas method causes any of the results that may be produced according to the probability distribution to be produced, without performing a calculation of the probability distribution in the time evolution calculation, so expression by a real value is completely unnecessary.

As one method for drastically increasing the saving of storage capacity and shortening of computation time in a multiscale fluid analysis, eliminating any representation of real values would be very effective, as will be explained in section 4.2 below. Accordingly, the author considers **“a model with no real-number representation that saves storage capacity and accelerates the time evolution calculation”** to be the guiding principle for substantially accelerating the multiscale fluid analysis. Because the “virtual particle model” of the “lattice gas method^{9) 10)}” satisfies this condition, it was chosen as the starting point for the discussion.

There is also another approach which drastically increases storage capacity saving and shortening of computation time. That approach is to finely arrange the lattice points in regions where the diameter of the smallest vortex is small, such as the area surrounding the structure, and to coarsely arrange the lattice points in regions which are distant from the structure, where the diameter of the smallest vortex is large. While this approach makes it possible to reduce the total number of lattice points, it has the drawback that the calculation is generally more troublesome in unstructured lattices where the grid-point array is irregular in parts where the sparseness/density of the lattice point arrangement changes. Therefore, an approach of hierarchically arranging lattices that have a regular structure and differ only in sparseness/density is adopted. The “building-cube method (BCM)” is known as a typical approach of this type which is used in ordinary computational fluid dynamics (CFD).

Concerning the lattice gas method, Robert P. Bosch, Jr. had already devised a similar approach in 1993 in a dissertation entitled “A Multigrid Algorithm for Lattice Gases¹¹⁾”. In Bosch’s lattice point arrangement method, a “heavy virtual particle capable of moving only a coarse grid point network” and a “light virtual particle capable of moving only a fine grid point network” are mutually converted on a lattice point located in a connection region where the coarse grid point network is linked with the fine grid point network. In this conversion, the mass and momentum of the “heavy virtual particle” must be equal to the sum of the masses and momenta of the multiple “light virtual particles” to be converted with it. However, the probability that a “heavy virtual particle” that satisfies this condition and multiple “light virtual particles” will simultaneously arrive at the same position is extremely low. Therefore, a generation and annihilation process for a virtual particle having a negative mass is introduced in the process of conversion between a “heavy virtual particle” and “light virtual particles” to ensure that the local conservation law for mass and momentum is satisfied at all times. The present paper assumes the use of this “multigrid algorithm.”

4.1.2 Outline of Lattice Gas Method/Four-Dimensional FCHC Model

This section explains a specific model of the lattice gas method. In lattice gas method fluid analysis, lattice points are regularly arranged in a space where a fluid is present, and many virtual particles, each having a certain mass and momentum, move while repeating ① “collision scattering” on lattice points and ② “translational movement” between lattice points. These states are averaged in order to determine the behavior of macro fluid physical quantities (e.g., density, momentum, velocity) (cf. Fig. 3). As long as a particle collision in which the mass and momentum of the virtual particles are conserved before and after the collision scattering in this process is assumed, the behavior will be quite similar to the fluid behavior under certain conditions in nature. However, unlike fluid molecules in nature, the velocities of virtual particles cannot take continuous values. Therefore, the macro behaviors derived by the lattice gas method will be slightly different from the fluid behavior derived by general computational fluid dynamics (CFD), which assumes a continuum fluid. A calculation method for dissolving this “slight difference” was devised by Christopher M. Teixeira in 1993¹²⁾, and the lattice gas method has now become a fluid analysis approach which also offers accuracy equivalent to CFD in theoretical terms¹³⁾.

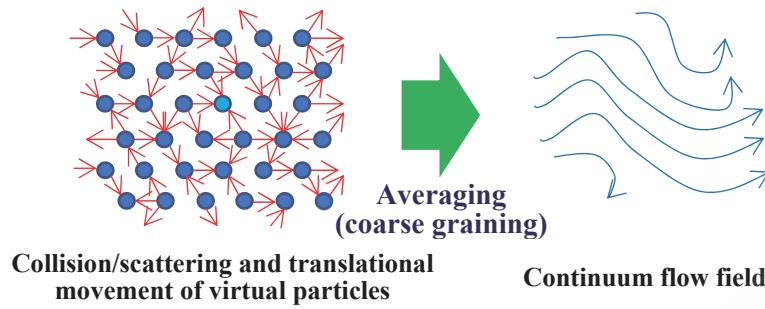


Fig. 3 Simulating of a continuum flow field by averaging the behaviors of virtual particles

Particularly in the case of Teixeira’s “lattice gas method/FCHC 54-velocity model”¹²⁾, Teixeira’s dissertation indicates that if the calculation result is compared with the calculation result by CFD for an incompressible fluid, the former is theoretically consistent with the latter up to the third-order accuracy for Mach numbers. In this model, one lattice point can accommodate “up to 6 stationary particles, a total of 24 slow particles consisting of one particle each in 24 different directions, and a total of 24 fast particles consisting of one particle each in 24 different directions, making a grand total of up to 54 (= 6 + 24 + 24)” virtual particles. Any lattice point arrangement where virtual particles can exist maintains the isotropy of the stress tensor. Therefore, Teixeira adopts a “four-dimensional face-centered hypercubic lattice (FCHC lattice).” The following presents the main points of the model and simulation examples (cf. Figs. 4, 5 and 6).

[Reference] Main Points of Teixeira’s Lattice Gas Method/54-Velocity Model

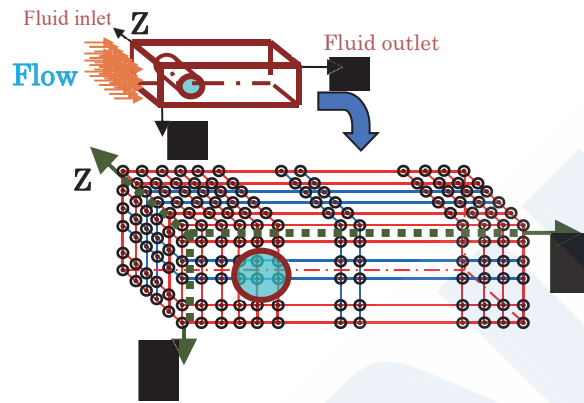
- (1) All virtual particles have the same mass ($m[\text{kg}]$).
- (2) Each virtual particle moves in synchronization translationally on the lattice points of a “face-centered hypercubic (FCHC) lattice,” where $\Delta L [\text{m}]$ is the smallest lattice point interval that exists in the four-dimensional space, at a certain time step interval ($\Delta \tau [\text{s}]$), and has a four-dimensional velocity $\vec{C}_{ji} [\text{m/s}]$ (energy: $\varepsilon_{ji} \equiv (1/2)m(\vec{C}_{ji} \cdot \vec{C}_{ji}) [\text{J}]$, velocity direction: i) which is necessary to realize that move.

The possible velocities of the virtual particle are as follows:

- ① Particles with 0 energy: number of particles that can exist $d_0 = 6$.
 $\vec{C}_{ji} = (0,0,0,0) [\text{m/sec}]$ (\leftarrow stationary particles)
 - ② Particles with energy $mc^2 [\text{J}]$: possible velocities $d_1 = 24$ velocities
 $\vec{C}_{ji} = (\pm c, \pm c, 0, 0), (\pm c, 0, \pm c, 0), (\pm c, 0, 0, \pm c), (0, \pm c, \pm c, 0), (0, \pm c, 0, \pm c), (0, 0, \pm c, \pm c) [\text{m/s}]$
 where, $c \equiv \Delta L / \Delta \tau [\text{m/sec}]$
 - ③ Particles with energy $2mc^2 [\text{J}]$: possible velocities $d_2 = 24$ velocities
 $\vec{C}_{ji} = (\pm 2c, 0, 0, 0), (0, \pm 2c, 0, 0), (0, 0, \pm 2c, 0), (0, 0, 0, \pm 2c), (\pm c, \pm c, \pm c, \pm c) [\text{m/s}]$
- (3) No more than two virtual particles with the same velocity can be present on the same lattice point at the same time.
 - (4) Interaction (collision scattering) between virtual particles occurs only on a lattice point, and the collision rule under which the sum of the mass, momentum and energy of the virtual particle is conserved is probabilistically applied before and after occurrence of collision scattering.
 - (5) The probability of transition between the states of existence of the virtual particles that can mutually transition by collision scattering is equal in both directions.

[Example of lattice point composition when lattice gas method/54-velocity model is applied]

A large number of lattice points are arranged in directions X, Y and Z in a three-dimensional space, and a rectangular grid-point array is created. It is assumed that each grid point has the freedom to identify the positions of $R = 0, 1, 2, 3$ as the four-dimensional coordinates inside it. The figure below illustrates this, and shows the appearance of a four-dimensional face-centered hypercubic lattice projected in a three-dimensional space. In the numerical simulation, for example, the lattice comprises 1024 lattice points arranged in the X direction, 192 lattice points in the Y direction and 384 lattice points in the Z direction as a three-dimensional degenerate lattice.



[Example of conditions setting for transient change simulation]

At time step 0, that is, at the start of the simulated calculation, arrange virtual particles numbering 20% of the maximum number of virtual particles that can be present at each lattice point in a random direction. As a result, the macro flow velocity that can be obtained through coarse graining will be 0, and the fluid is stationary in a cubic shape. Next, at time step 1, start injecting virtual particles having a velocity in the +X direction at the $X = 0$ position. Then, as time progresses, the entire fluid will have a macro velocity in the +X direction. At that time, at a rectangular outlet that exists beyond the +X side, a boundary condition, under which the virtual particle arrangement on a lattice point immediately anterior to the outlet is copied to the virtual particle arrangement on a lattice point immediately posterior to the outlet, was approximately established, while in the $\pm Y$ and $\pm Z$ directions, a periodic boundary condition was adopted. An “infinitely long cylinder having a central axis in the Z direction” was placed in a position close to the inlet in this flow, and the fluid behavior occurring in the wake flow was calculated. Snapshot images are selected from the moving images of the transient changes in the momentum distribution coarsely grained on the cross section, and are represented.

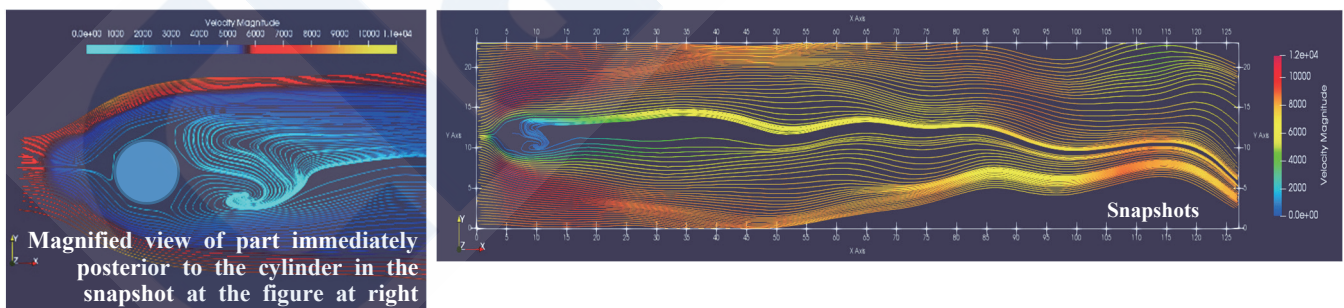


Fig. 4 Simulation of transient changes of the wake flow of a cylinder ¹⁴⁾

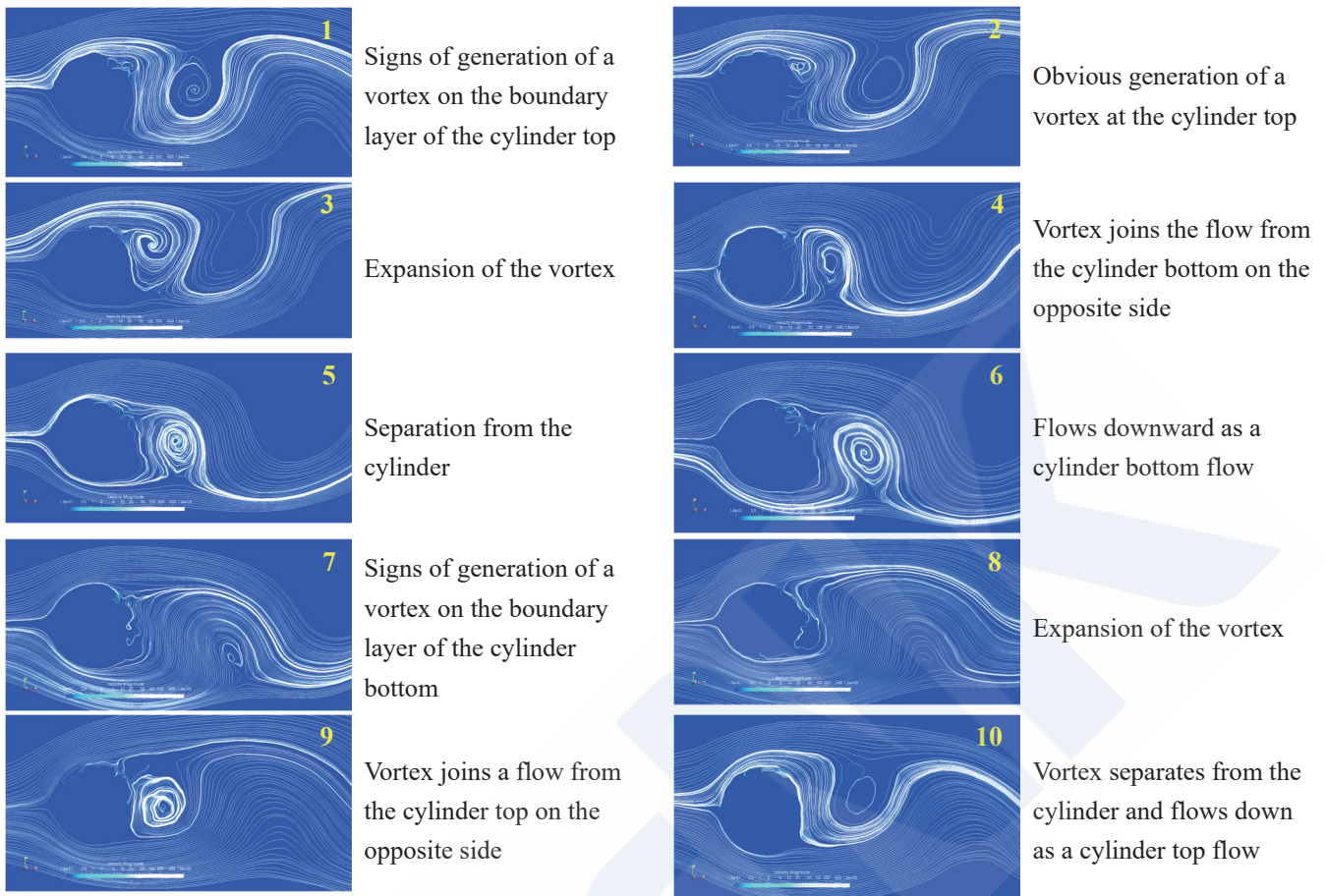
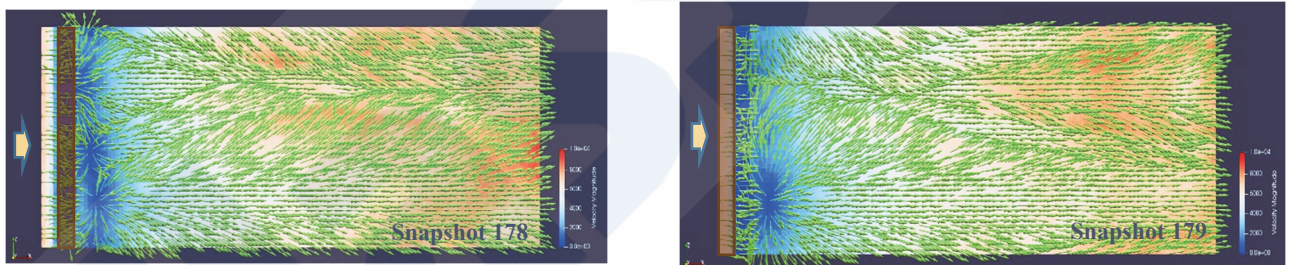


Fig. 5 Alternating vortex shedding from the cylinder boundary layer ¹⁵⁾



The above figures concern the flow velocity on a plane formed by the flow direction and the cylinder axis, where the magnitude of the flow velocity is shown by the background color and the direction of the flow velocity is shown by the green arrows. A dead water region is present immediately behind the cylinder (indicated by the brown rectangle) on the left end (right side of the cylinder in the above figure).

If the moving images are observed, when a sufficient time has passed after the flow becomes a Karman vortex, regions of a low-velocity fluid (blue part) and a medium-velocity fluid (light-blue part) appear alternately in the cylinder axial direction and sway quite violently in that direction. Further downstream, the images display a state where a “part in which the downstream flows converge, accelerating the flow velocity” and a “part in which the flows spread, slowing the flow velocity” are arranged alternately in the cylinder axial direction, and temporal wavy undulation, while swinging the flow direction, was observed. This fluid behavior considered to have occurred due to a combination of streams called high-speed streak and low-speed streak, and the effect of a “vertical vortex with a rotational axis in the downstream direction.”

Fig. 6 Vertical vortices generated in the wake flow of a cylinder ¹⁴⁾

4.2 Collective Calculation of 16384 Lattice Points with a Vector Core

If all the state quantities representing the state of virtual particles are discretized into a finite number to completely eliminate real-number representations, real number calculation in a time evolution calculation would become unnecessary. If a real computer is to memorize one real number, a 32-, 64- or 128-bit memory is required, depending on the accuracy. Therefore, in order to calculate the temporal change of one real number, it is essential to occupy a 32-, 64- or 128-bit width in the arithmetic circuit. By contrast, if the state quantities of virtual particles are discretized into a finite number for representation, the only requirement would be, for example, to allocate codes such as A, B, C and so on in ascending order to the values of the state quantities, and if the value of the state quantity is B, to memorize a one-bit value of $B = 1$ instead of memorizing the real value of B itself. If the value of the state quantity is not B, the computer will memorize $B = 0$. This will realize a substantial saving of storage capacity.

In addition, if two arriving particles having velocities D and E at a lattice point become two starting particles with velocities F and G ($D + E \Rightarrow F + G$) due to collision scattering, the two arriving particles with velocity D and velocity E have ceased to exist due to collision scattering, and they no longer have those velocities. Therefore, computation processes $D = 1 \Rightarrow D = 0$ and $E = 1 \Rightarrow E = 0$ will be performed. Similarly, because two starting particles having velocities F and G are generated through collision scattering, the computation processes $F = 0 \Rightarrow F = 1$ and $G = 0 \Rightarrow G = 1$ will also be performed. In any of these computation processes, the variables D, E, F and G can only take a value 1 or 0. Therefore, in the arithmetic circuit, it is only necessary to always occupy one-bit width. Accordingly, the decision made is to perform calculations of changes D, E, F, G, ... at one lattice point constantly corresponding to a certain bit in the arithmetic circuit in sequence. This makes it possible to perform parallel time evolution operations collectively for the same number of lattice points as the number of bits that can be processed collectively using one arithmetic instruction.

The Tohoku University Cyberscience Center vector computer AOBA-A (SX-Aurora TSUBASA, manufactured by NEC), which the author uses, is capable of processing data of $64 \text{ bits/word} \times 256 \text{ words/instruction} = 16384 \text{ bits/instruction}$ per vector processor core by issuing one vector instruction. Therefore, a single vector processor core is capable of performing collective calculations for 16384 lattice points (the capacity of one CPU with 8 cores is 8 times larger).

In addition, as of 2013, it was confirmed that this collective calculation approach can process time evolution calculations for 100 billion lattice points using 64 nodes (512 CPUs, total main storage: approx. 8 TB) of the Earth Simulator (ES2 = SX-9)¹⁶⁾.

In some cases, it is also possible to achieve real-time calculation by using this calculation method. The author was responsible for the startup of operation of the supercomputer “K,” and conducted an analytical evaluation of an air-cooling wind field for supercomputer racks arranged in a computer room with an area of approximately $50 \text{ m} \times 60 \text{ m}$ ¹⁷⁾. The conclusion at that time was that a computer with approximately 10 teraflops (approximately one rack of supercomputer K) would be capable of performing real-time simulation of an air-cooling wind field for a large-scale computer if the division of lattice points is approximately $1,024 \times 1,024 \times 256 \approx 260$ million. There are also cases where real-time simulation is possible simply by the effect of 1 lattice point, 1 bit width operation, provided a certain level of resolution is acceptable.

4.3 Calculating Values for Any Turbulence with No Real Number Calculation

The lattice gas method has an important advantage from the viewpoint of stable calculation of violently changing flows such as turbulence. As described above, all real number representations can be eliminated in time evolution calculations by the lattice gas method, and in this case, no truncation error resulting from floating-point operation will occur. Therefore, arithmetic failure will not occur during the calculation, and it will be possible to stably continue to find some kind of calculation result, regardless of how violent the flow is.

Although turbulent states generally occurs under a large Reynolds number condition, on the other hand, it has been confirmed that this method is capable of expressing not only positive fluid viscosity, but also negative fluid viscosity, as will be described in section 5.3 below. If these mechanisms for expressing viscosity are properly adjusted, it will be possible to simulate even a state with a very large Reynolds number by expressing the positive fluid viscosity of a value extremely close to zero. This method is also considered to be very advantageous for application to turbulence analysis from this viewpoint. For the idea of using “negative viscosity expression” with the lattice gas method for turbulence analysis, please refer to Rothman’s dissertation¹⁸⁾.

4.4 Many-Worlds Probability Bit Operation with a Quantum Computer

The collision scattering calculation in the lattice gas method is a calculation which converts a bit string representing the presence or absence of arriving particles having various velocities to a bit string representing the presence or absence of any

starting particle, as described in section 4.2. At this time, the bit string of the starting particle that becomes the output of collision scattering calculation can be generated in any bit string in a physical sense, as long as the sum of the mass and the momentum is conserved before and after the collision scattering. Therefore, multiple starting particle bit strings can generally be output for one arriving particle bit string. In individual calculations, the only requirement is to determine only one starting particle bit string, among the multiple possibilities, according to a certain probability. Such an arithmetic characteristic is simply the arithmetic property of a “gate-based quantum computer,” which uses quantum bits (qubits)¹⁹⁾. In other words, in the world where quantum mechanics is applied, state change progresses concurrently in many-worlds, and a result of change in any one of the worlds is produced probabilistically at the instant it is observed.

Currently, research and development of quantum computers toward practical use is being pursued at major companies, universities, etc. around the world, and their open use has also begun. Although the author considers use of the “gate-based quantum computer” to be promising, the number of qubits that can be interconnected is still small due to the “quantum entanglement phenomenon.” However, IBM’s Q System¹⁹⁾, which became famous in 2019, when Google demonstrated that a quantum computer could solve a problem in only 200 seconds, which would require 10000 years with the fastest supercomputer, also showed this performance even at 53 qubits. Moreover, the quantum computer also has good compatibility with qubit computation, which is specific to the lattice gas method; for example, “direct transition of the bit operation of the lattice gas method to qubit computation is easy (cf. Fig. 7)” and “the lattice gas method, which finds a physical quantity through a statistically average calculation, can ensure reliability within its own limitations, even though the error rate of the quantum computer is not zero.” Thus, the quantum computer is expected to have great potential for use in achieving low-power-consumption, massively parallel computing in the future.

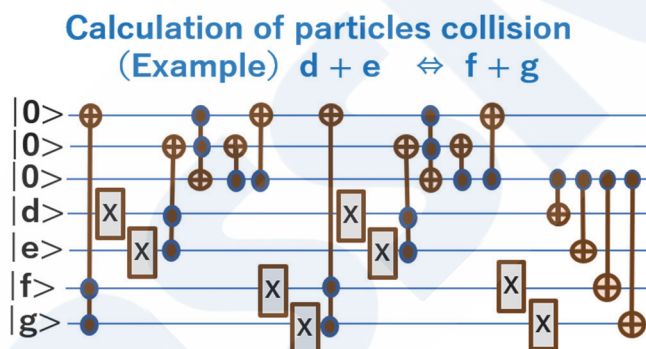


Fig. 7 Image of computation with gate-based quantum computer

[Panoramic perspective] Focus on Brain-Inspired Computing

Among the three cases described in section 2.1, the “ocean energy harvesting vessel” represents the most dynamic movement of the system itself under the influence of the natural environment. Even in such a situation, a human (for example, a master yachtsman) would manage to handle the ship properly in real time. Therefore, the author decided to search for hints in “brain-inspired computing,” like that which the human brain performs.

A third artificial intelligence (AI) boom has now arrived. Although the impetus for this boom was the success of deep learning, various studies of AI from diverse angles were conducted long before this boom, but we are still far from elucidating the essential mechanism of expression of the brain functions.

In the meantime, systems which are capable of expressing a property similar to the mechanism of expression of functions in an actual brain have been developed, even though the mechanisms are different, and some of those technologies have developed in scale to engineering applications and have been adopted widely in society. The following focuses on “fuzzy inference” and “multi-layer perceptron learning” as representative examples of those technologies.

5. AIMING AT REALIZING MULTI-PHYSICS COUPLING (Proposal of Simplified Model for Intuiting Physical Behavior)

5.1 Same Calculations for Physics with Different Virtual Particle Pictures

The essence of fuzzy inference is not the fuzzy inference rule itself, but the rough “image model” that an expert in the field draws in their head when deriving that rule. This “image model” is not the real, complex system which is subject of discussion. It is a simple image model that is visual in many cases. However, an expert in the field would be able to derive the actual system behavior intuitively and semi-quantitatively by imagining the behavior of this image model. In other words, the model becomes a “surrogate model” that plays the role of “surrogation,” for example for a differential equation that drives time evolution calculation. Therefore, the author considered that **“being a simple image model which makes it possible to infer semi-quantitatively the causality of physical behavior”** should be the primary condition for an AI surrogate model.

In this paper, a “virtual particle picture” is adopted as a specific example of a “simple image model.” An image model for “collision scattering” and “translational movement” of a virtual particle that is based on the lattice gas method is itself a general-purpose “virtual particle picture,” and is adaptable to various physical phenomena. For example, assume the application of a collision scattering rule which requires that any lattice point group in a certain region should be inverted regardless of the direction of an arriving particle, so that the particle returns in the direction from which it came. Under this assumption, any virtual particle in that region is static on a time average basis in macro terms, and thus can be interpreted as representing a fixed solid region. This is the simplest example showing that the model can simulate both fluid and solid behaviors using the same calculation.

5.2 Achieving Zero Delay Resulting from Coupling by Conducting Solid-Fluid Coupling Analysis

Now, let us consider moving the position of a lattice point, which is subject the collision scattering rule for expressing the characteristics of the solid described above, according to the “magnitude and the direction of an ‘impulse’ applied to that point by a virtual particle arriving from the surrounding area in the course of collision scattering.” If this is adjusted skillfully, it should be possible to simulate even the deformation of an elastic body. In this way, multi-physics physical phenomena are interpreted by a unified “single physics” of interaction between particles, and the time evolution calculation is performed using the same calculation regardless of whether the substance is a fluid or solid. This should ensure that no essential delay will occur in comparison with the calculation time in cases where the entire substance is a fluid.

Currently, the most successful approach for this kind of “virtual particle picture” seems to be the “particle method”⁸⁾. The approach used in the particle method is to find a solution to how individual fluid masses move according to the lapse of time by solving a motion equation for each fluid mass. Therefore, this method is also capable of simulating “major deformation of a fluid” and “fragmentation of a fluid due to collision.” In other words, since the method models substances as an aggregate of small masses, free handling of major changes in the motion or shape of a substances is possible. For this reason, the particle method is extensively applied not only in fluid analysis, but also in structural analysis and solid analysis.

The essential reason why a fluid mass (virtual particle) can move freely in the “lattice method” is because it is a “meshless solver” with no lattice to constrain the positions where virtual particles can exist. By contrast, in the “lattice gas method,” the positions where virtual particles can exist are limited to regularly-arranged lattice points. However, this does not mean that the movements of virtual particles are limited in the direction of the lattice axis. For example, in the case of “Teixeira’s 54-velocity FCHC model,” virtual particles can protrude from each lattice point in 48 different directions, which allows quite large freedom of movement. Thus, if there are successful cases of multi-physics simulation by the “particle method,” it thought that the benefits of this method were achieved by direct application of that innovation.

5.3 Controlling Viscosity by the Probability of Entrainment in a Starting Particle Group

A virtual particle in fact represents an extremely large number of real molecules. An “arriving particle” and “starting particle” before and after collision scattering is in fact particle groups consisting of many real molecules acting as a group. In the case of a liquid, the density is not greatly different from that of a solid, and even gases will behave as an incompressible fluid if the Mach number is sufficiently small. In other words, real molecules move while clustering very closely together, and would also move to fill any vacant space that might be created. Expanding this image, it is possible to establish a “fuzzy inference” to the effect that “If there is a virtual particle that starts to move in a certain direction in the previous collision scattering, it will be drawn into the previous starting particle group, and the number of real molecules that are forcibly entrained in that direction

will increase, even if virtual particle(s) attempt to fly out in another direction in this collision scattering.” This means that the probability that the starting particle in this collision scattering is synchronized with the direction of the starting particle in the previous collision scattering will increase. Based on many case studies, the author has confirmed that fluid viscosity can be controlled over a wide range by changing this “synchronous entrainment probability”²⁰⁾ (cf. Fig. 8). In this type of control, care must be taken to ensure that conservation of momentum is maintained on a time average, and it is possible to express negative viscosity (including spontaneous generation of a vortex from a stationary fluid).

In fluidics for manufacturing, if Reynolds numbers ranging from a Reynolds number on the experimental and prototyping scale to a Reynolds number on the real machine scale can be continuously simulated, the reliability of prediction will increase, making it possible to perform engineering design with higher confidence. In this sense, the ability to provide a wide range of fluid viscosities by a simple method is an enormous advantage.

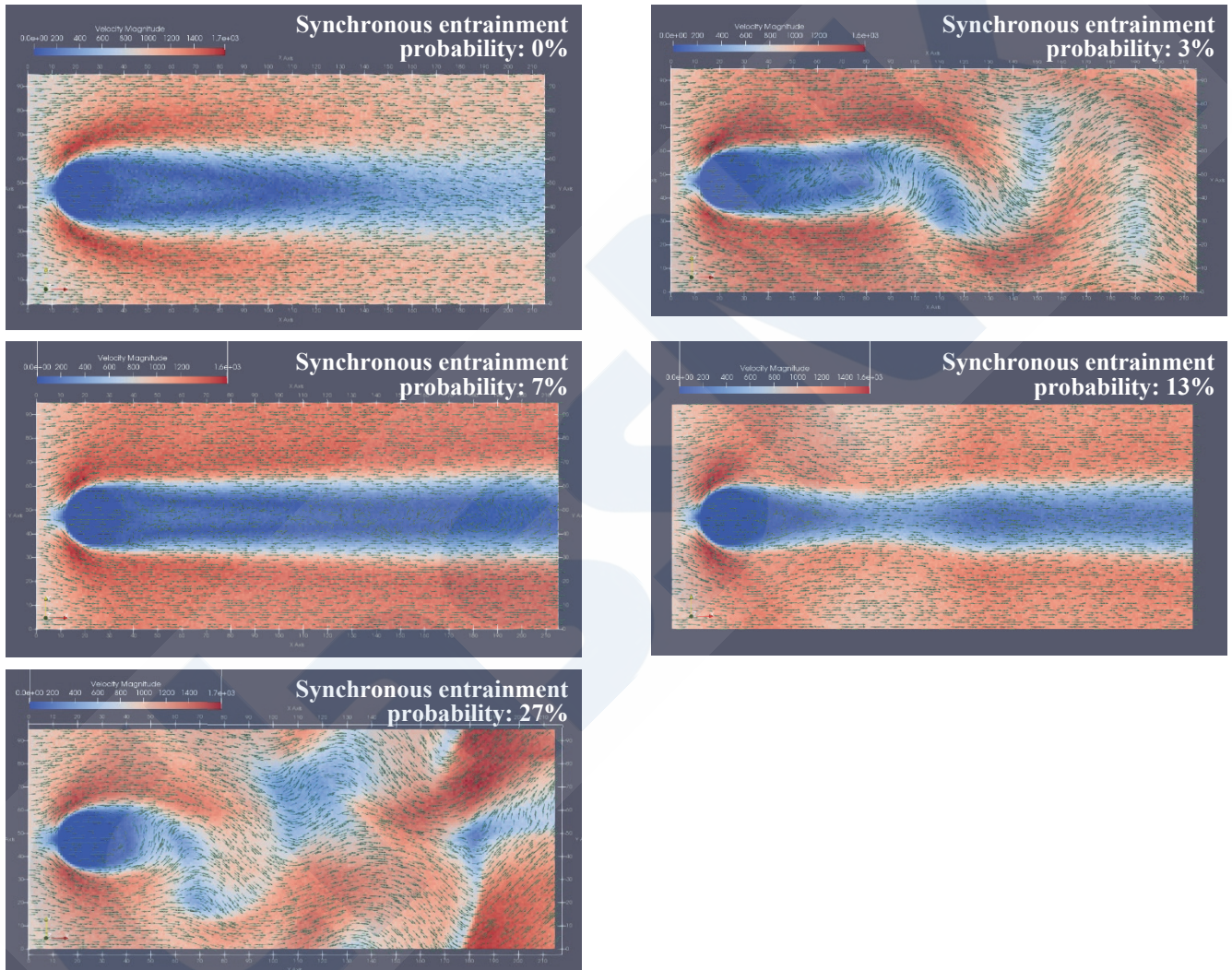


Fig. 8 Viscosity control by changing the probability of synchronous entrainment operation²⁰⁾

5.4 Predicting Crack Propagation by Results of the Particle Method

Among the applications of the particle method, simulations are also conducted in dynamic elasticity analysis and crack propagation analysis⁸⁾. Since the small masses that constitute the substance of interest are separated, it is possible to simulate the growth of cracks. In examples of the particle method, it is considered that a particle of a substance will fracture when the von Mises stress (or strain) of the particle reaches the fracture stress (or fracture strain) due to stress concentration. Since stress distribution is no longer possible under this condition, the fractured particle will become the particles that form the crack face. Here, it is sufficient to employ ingenuity to realize a calculation method using the virtual particles of the lattice gas method. In real structures such as windmills, problems caused by the generation of cracks are a frequent occurrence. As this suggests, an analysis which also includes prediction of crack propagation in a fluid-solid coupling analysis would have major practical advantages.

6. AIMING AT REALIZING AN IMMEDIATE RESPONSE TO THE REAL WORLD (Proposal of Simplified Model with Learning Computation)

6.1 No-Delay Learning with a Recurrent Neural Network

The “multi-layer perceptron (hierarchical neural network)” is the type of artificial neural network whose use in society has advanced most. This category also includes neural networks that are capable of performing “deep learning.” The learning function of the multi-layer perceptron is the “error back-propagation method,” which triggered of the second AI boom, and its general theory and engineering applications were already established at that time.

With the lattice gas method, a macro physical property value can be obtained from the sum or statistical average of the masses and momenta possessed by virtual particles in its vicinity. Since the computation of this sum or average can also be represented by the computational structure of a multi-layer perceptron, the hierarchical structure of the neural network that computes the time evolution also contains a “multi-layer perceptron that outputs a macro physical property value.”

If a computed output value which is consistent with the measurement data is desired, the neural network traces back to the cause of the difference between the computed output value and the measurement target value, and corrects the weights of neurons located on that trace-back path according to the procedures of the above-mentioned “error back-propagation method.” By repeating this process, the computed output value can be made to approach the measurement target value, which is the teacher datum. In other words, if a computational structure for recurring the data from the second stage of the multi-layer perceptron to the first stage (recurrent neural network: RNN) is built, a means of “data assimilation” can be acquired automatically. For this reason, the author thinks that **“being a model that can be replaced with the computational structure of a recurrent neural network having a learning function”** is the second condition for an AI surrogate model.

Here, a new weight derived from the difference between the computed output value and the measurement target value at time “ t ” is reflected in the computation after time “ $t + \Delta t$.” It should be noted that the network does not perform the computation by tracing back to the past. Therefore, in this method it is important that “feeding back measurement data to the simulation will not delay the original time evolution computation.”

6.2 Data Assimilation without Stopping Time Evolution Computation

If the method described in the preceding section is applied to a multi-layer perceptron that performs computations in the lattice gas method, data assimilation can be achieved without stopping the time evolution computation. The following shows that in this case all computations of the multi-layer perceptron structure can be performed within a range of very small integers without using real numbers.

First, the lattice points are arranged regularly in a physical space, and each lattice point is considered to contain a multi-layer perceptron (cf. Figs. 9 and 10). In the lattice gas method 54-velocity model, 6 particles are stationary particles and therefore cannot move. This means there can be “arriving particles” from a maximum of 48 ($= 54 - 6$) lattice points located in the vicinity. Information on their presence or absence at that time, for example, “1” if an arriving particle is present, “-1” if absent and “0” if unknown, is input in the input layer of the “multi-layer perceptron,” and a value (1, -1) calculated by a “sum-of-product threshold computation” of the neural network appears in the output layer. If this information is “1,” a starting particle from the respective lattice point is present, and if it is “-1,” a starting particle is not present.

The macro physical quantity to be observed at a certain location in space is calculated from the total sum of the masses, momenta and energies of the virtual particles in an appropriate vicinity around that location. Therefore, even with a neural network that performs this computation, only very small integers will appear.

Furthermore, if the lattice points where virtual particles can travel are all interconnected, the “entire flow field” can also be represented by the neural network, and a time evolution computation can be performed. In other words, any change in the “flow field” can be considered as the group behavior of the “virtual particles” travelling between a “space lattice containing a neural network (multi-layer perceptron)” and its lattice point (neuron) (cf. Fig. 11).

As described in the preceding section, if measurement data are obtained at several spatial positions in the real world, the “multi-layer perceptron” contained in neighboring lattice points of the respective positions will execute error back-propagation to make the computed output value consistent with the measurement data. At that time, it is assumed that the value of the “weight” by which the input data of the multi-layer perceptron is to be multiplied also can take only a value of “1, 0 or -1.” Learning is performed to adjust the probability of adoption of those weights. In short, rough adjustment is made by selecting an individual

weight from “1, 0 or -1,” and fine adjustment is achieved through adjustment of the probability of adoption of those weights. If this weight adjustment process is continued, the simulated data can be expected to become consistent with the measurement data to some extent, although this will also depend on the condition of change in the measurement data.

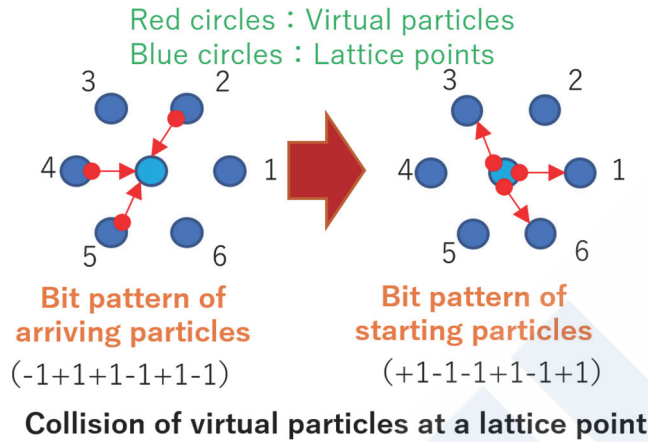


Fig. 9 Change in information on presence or absence due to collision scattering²⁰⁾
(in case of a two-dimensional lattice gas method FHP model)

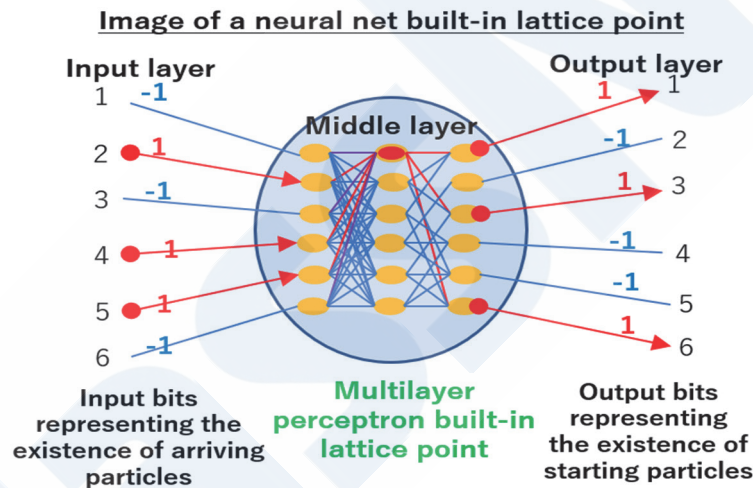
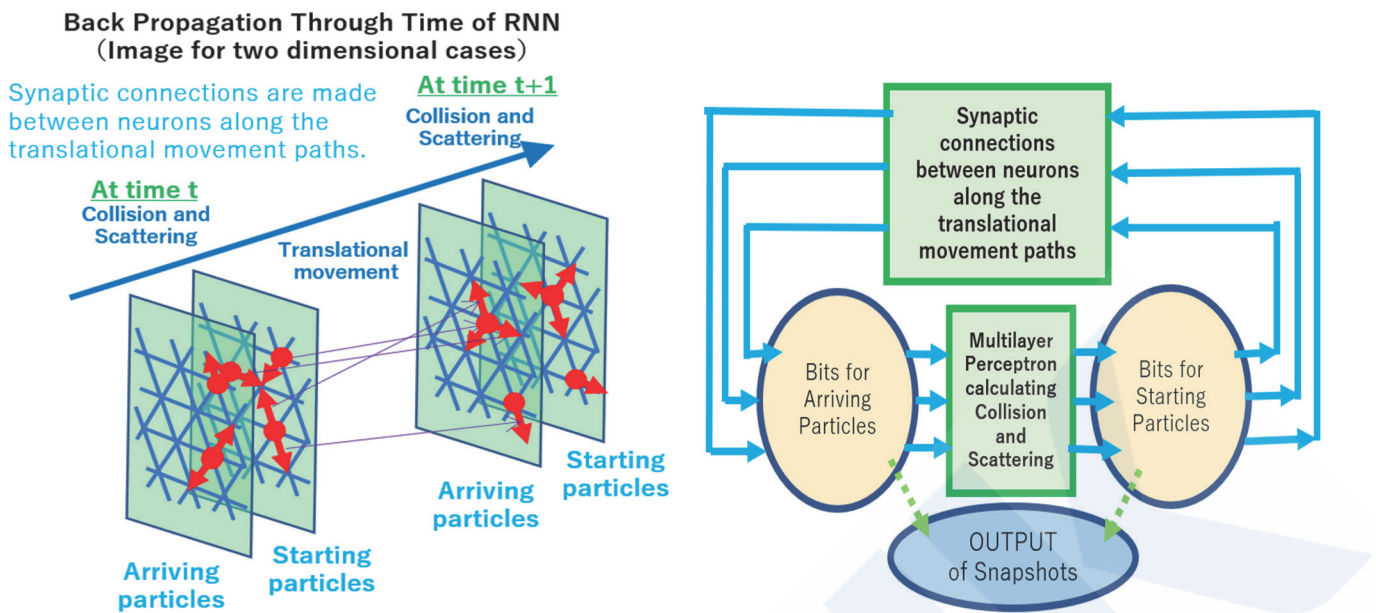


Fig. 10 Multi-layer perceptron for calculation of collision scattering²⁰⁾

In Fig. 10, the input layer conveys an input value ± 1 as-is to the intermediate layer, and the intermediate layer identifies the input bit string. For example, if a weight of +1 is set for the red line input and a weight of -1 is set for the purple line input on the top red neuron of the intermediate layer, a weight string consisting of purple (-1) \rightarrow red (+1) \rightarrow purple (-1) \rightarrow red (+1) \rightarrow red (+1) \rightarrow purple (-1) is formed in that order from the top. At this time, the sum of products is the maximum value (6) only when the input bit string to the input layer coincides with this weight layer. The intermediate layer identifies this by converting the activating function of the intermediate layer neuron to a step function with a threshold of 6. The output of this neuron is connected only to neurons 1, 3 and 6, which are the neurons that should be activated in the output layer. In the neurons in the output layer, the input weights of the connected synapses are all set to +1, and the activating function is converted to a step function with a threshold of -1. As a result of this, if any one of the inputs becomes +1, the neuron will be activated (output = +1). In actual application, these layers must be stacked in multiple stages. Further, if the collision rule is to be probabilistically applied, the number of neurons in the input layer is increased and an input of ± 1 is given randomly.



6.3 Robust Learning of Even Incomplete Real-World Measurement Data

Actual measurement information which is to be acquired from the real world normally cannot be acquired completely at all boundaries due to factors such as restrictions related to measurement system installation or the occurrence of failures, and thus may contain erroneous data.

The operation of a neural network generally involves repetition of weighted addition of a large number of input values and operation of their thresholds. Therefore, even if a datum that should serve as one input value of one neuron is lost or erroneous information is input, there is a high possibility that its impact will be eliminated in the course of the computational process. Since this type of robustness in a computational process is expected to have a certain effect in cases where the incompleteness of the actual measurement information occurs as temporal-spatial dispersion, this approach is suitable for real-world data processing.

[Panoramic Perspective] Departing from the Differential Equation Solution

The most important point when considering fluidics analysis in the real world is that “it is impossible to predict any future change in the boundary conditions in advance.” Since boundary conditions are subject to the effects of changes in the conditions outside the boundary (i.e., in the outside world), it goes without saying that such changes cannot be predicted in advance unless all environments, including the outside world, are simulated accurately. For this reason, regardless of how accurately the initial conditions conform to reality when a computation is started, it is impossible to continue forever to predict the future state in the real world with high accuracy without feeding back information about the outside world. With this as a major premise, if correspondence with the real world is a priority, the natural idea would be to depart from the conventional approach of “solving a differential equation as accurately as possible,” and substitute a time evolution computation by an AI-based approach, namely, “(having the system) simulate the functions of the human brain and perform prompt feedback correction based on rough, fast inferences and measurement information about the outside world.”

6.4 High-Speed Computation between Distributions of Dimensionally-Compressed State Quantities

When AI is mentioned, the first key phrase that comes to mind today is “deep learning.” Therefore, let us first consider the concept of the “AI surrogate model,” which applies “deep learning” based on ordinary computation fluid dynamics (CFD), and not the lattice gas method (cf. Fig. 12).

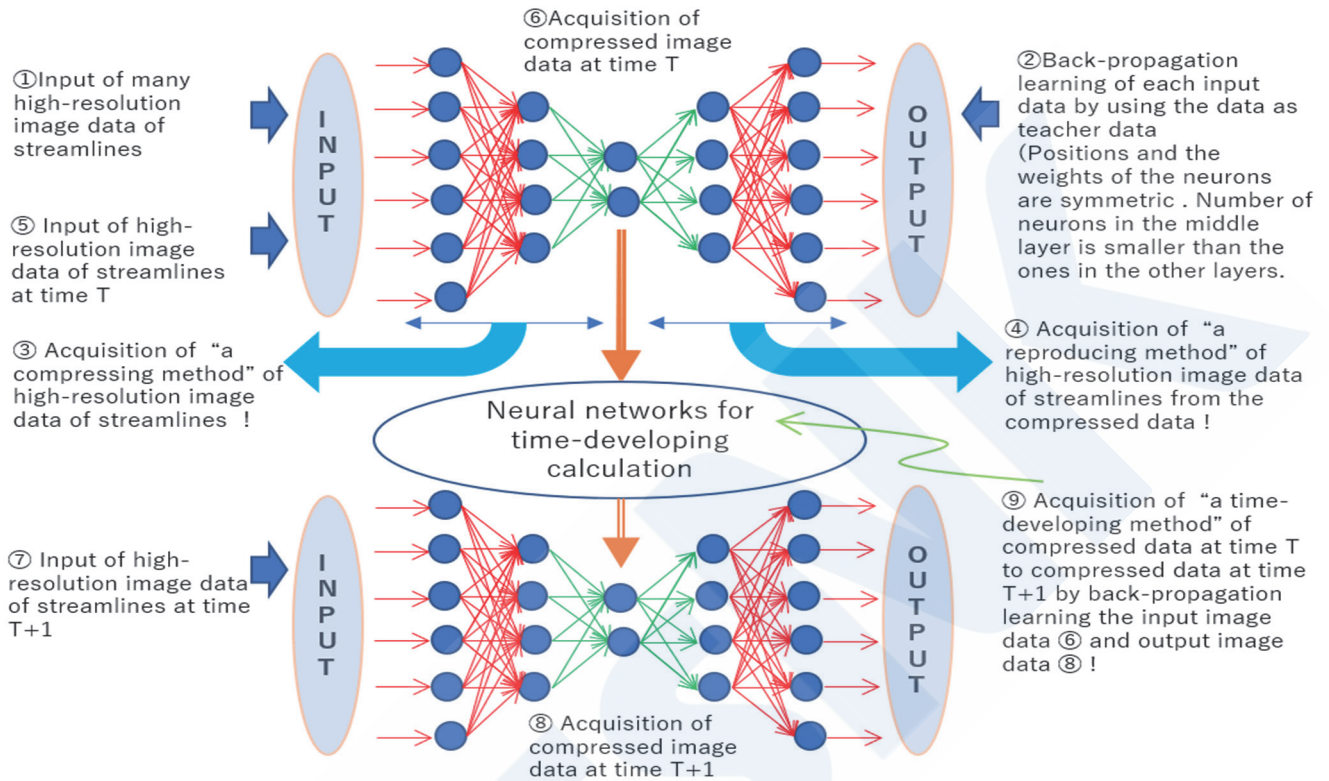


Fig. 12 Information-compressed type time evolution computation

To overcome the challenges of multiscale analysis, the first step is to perform a high-resolution time evolution computation based on the Navier-Stokes equation (NS equation), while utilizing the capability performance of a supercomputer to perform computations on an extremely large scale. This makes it possible to acquire very many sets of “detailed flow velocity space distributions at time t ” and “detailed flow velocity space distributions at time $t+\Delta t$ ”, even in a single computation. The next step is to dimensionally compress the flow velocity space distribution at each time acquired by this computation (huge three-dimensional array of three numeric values representing the respective components of the velocity vector) through deep learning, while utilizing the capability performance of the supercomputer to perform a very large number of parallel computations, provided they are of medium scale. By utilizing dimensional compression, the required storage capacity can be substantially reduced.

However, because the numerical value array obtained by dimensional compression is an array that is mechanically learned through computation by the neural network, a person seeing the numerical value distribution cannot understand its physical meaning by human intuition. The final step is to have the neural network learn a set of spatial distributions of flow velocities at the dimensionally-compressed times “ t ” and “ $t+\Delta t$.” Although the number of input/output datasets is huge, since they are dimensionally compressed, the scale of computation required to learn each dataset does not exceed the medium level.

As a result of the above, the time evolution computation method for the dimensionally-compressed spatial distribution of flow velocities was learned as a computation method of a neural network. This is one of the concepts of the “AI surrogate model,” which substitutes for the time evolution computation using the NS equation.

Incidentally, if a time evolution computation is performed using this “AI surrogate model,” the data obtained directly at the respective times will still be meaningless, dimensionally-compressed data. However, when we want to know the snapshots in the course of the time evolution computation, a physical, a meaningful spatial distribution of flow velocities can be restored at the original high-resolution level at any time by reverse computation of the dimensional compression.

The “information-compressed time evolution computation” described above can also be applied as-is to data obtained by the lattice gas method. This can be considered as a problem of recognition of multi-dimensional images in which one pixel is represented by 54-bit information and information compression. The computation method for time evolution between such information-compressed images leads to the possibility of executing a higher resolution analysis of fluid behavior at a higher speed. Even if the intuitive meaning of the computation method cannot be understood directly at that time, there would be no particular difficulties in the stage of real-time control, unlike the design stage, where trial-and-error study is required.

The need for immediate response to the real world arises during system operation. In this case, a compact independent computer that can be incorporated in the system at the site and can acquire measurement data or an IoT edge computer that can be connected to the Internet, without relying on a supercomputer or the like, would be a more ideal solution. Future AI research might discover an innovative algorithm that will surpass deep learning and have a large impact from both the engineering and social viewpoints. Moreover, a processor capable of executing AI algorithms at high speed might also be developed. In any case, I look forward to seeing the replacement of fluid computations with the computational structure of the neural network, as the results of the future AI research would be immediately applicable.

7. CONCLUSION

The usual approach to numerical simulations in fluidics analysis for manufacturing is to first set the differential equation that governs the physical phenomenon and then compute its time evolution. While this is the most reasonable and reliable approach, a simulation with much higher performance continues to be desired for application in the real world. To realize this dramatic improvement in performance, this paper has examined an “AI surrogate model” that would substitute for the differential equation by departing from the time-honored royal road of “differential equation solution,” and has introduced this as one possibility. Since a prosaic style of description was adopted in this paper, the gist of the argument may not be explained clearly in some parts. Finally, therefore, the outline of the paper is summarized as follows.

“AI Surrogate Model” for Manufacturing by Fluidics

(1) EXPANSION OF WIND ENERGY UTILIZATION ANALYSIS IN THE FUTURE

【Present Status】 High-resolution prediction is needed in fluidics for wind energy

(2) SETTING A DREAM TARGET AND ATTEMPTING BACK-CASTING THINKING

【Ambitious Target】 Ideal resolution is a width of 5 to 6 digits per dimension

(3) AIMING AT REALIZING MULTISCALE HIGH-SPEED CALCULATION

(Proposal of a Simplified Model Eliminating All Real-Number Representations)

【Challenging Action】 Operation with One Lattice Point and One Bit Width for Sparse and Dense Lattices



【Direct Results】 Collective calculation of 16384 lattice points with a Vector Core

【Additional Results】 Calculating Values for Any Turbulence with No Real Number Calculation

【Future Expected Results】 Many-Worlds Probability Bit Operation with a Quantum Computer

(4) AIMING AT REALIZING MULT-PHYSICS COUPLING

(Proposal of Simplified Model for Intuiting Physical Behavior)

【Challenging Action】 Same Calculations for Physics with Different Virtual Particle Pictures



【Direct Results】 Achieving Zero Delay Resulting from Coupling by Conducting Solid-Fluid Coupling Analysis

【Additional Results】 Controlling Viscosity by the Probability of Entrainment in a Starting Particle Group

【Future Expected Results】 Predicting Crack Propagation by Utilizing the Achievement of Particle Method

(5) AIMING AT REALIZING IMMEDIATE RESPONSE TO THE REAL WORLD

(Proposal of Simplified Model with Learning Computation)

【Challenging Action】 No-Delay Learning with a Recurrent Neural Network



【Direct Results】 Data Assimilation without Stopping Time Evolution Computation

【Additional Results】 Robust Learning of Even Incomplete Real-World Measurement Data

【Future Expected Results】 High-Speed Computation between Distributions of Dimensionally-Compressed State Quantities

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In the course of the study described in this paper, many parameter studies were conducted using the vector supercomputers (e.g., SX-9, AOBA-A [SX-Aurora TSUBASA]) at the Tohoku University Cyberscience Center each time the author devised a candidate “AI surrogate model.” These computers easily demonstrate their performance in massively parallel computing with 1-lattice-point, 1-bit-width operation and are also very easy to use. I would like to take this opportunity to express my sincere gratitude to all those concerned at the Center for maintaining and improving the use environment for these state-of-the-art vector computers over a long period, and for providing generous guidance and cooperation whenever we had the occasion to use these facilities.

REFERENCES

* This paper is not a paper for presentation at any academic conference, but rather is an exposition. Therefore, the references listed here are explanatory references selected on a preferential basis, rather than original papers.

- 1) Mitsui O.S.K. Lines: “MOL Group’s Environmental Vision 2.1,” MOL website (<https://www.mol.co.jp>).
- 2) Kanda, Y. & Ishihara, T. “High-resolution direct simulation of turbulence”, *J. of Turbulence*, 7, pp. 1-17, 2006.
- 3) Matsuo: “Channel Flow”, *Flow* 22, pp. 35-40, 2003.
- 4) Tsubokura: “K Computer will Change the Automotive Development Process,” *World of Computational Science* No. 6, RIKEN AICS, 2013.
- 5) Nishikawa: “Running a Ship in the K Computer,” Vol. 14, *Keisan Hyakkei, RIST*, (hp150005: Practical Use of Towing Tank Alternative Technology with Direct Simulation of a Turbulence), 2015.
- 6) Yoshimura, et al: “Construction and Utilization of a Digital Twin for a Real-Machine Clean Energy System by Linking and Using a Super Simulation and AI”; Clean Energy “Fugaku” Project, Program for Accelerating the Generation of Results with “Fugaku.”
- 7) Tokuda, Matsuoka: “Real-time, Super-fast Computation --- Toward the Development of New Technology for Use of Computers ---,” *RIST News* No. 52, pp. 13-21, 2012.
- 8) Yagawa, Sakai: “Particle Method – Basics and Application,” 2016, Iwanami Shoten (ISBN 978-4-00-006150-6).
- 9) B. Haaslacher, U. Frisch, Y. Pomeau: “Lattice Gas Automata for the Navier-Stokes Equation,” *Physical Review Letters* Vol. 56, No. 14, pp. 1505-1508, 1986.
- 10) Uriel Frisch, Dominique d’Humières, Brosl Hasslacher, Pierre Lallemand, Yves Pomeau, Jean-Pierre Rivet: “Lattice Gas Hydrodynamics in Two and Three Dimensions,” *Complex Systems*, 1(1987), pp. 649-707, 1987.
- 11) Robert P. Bosch, Jr.: “A Multigrid Algorithm for Lattice Gases,” MIT, 1993.
- 12) Christopher M. Teixeira: “Continuum Limit of Lattice Gas Fluid Dynamics,” MIT, 1993.
- 13) Matsuoka: “A High-accuracy Fluid Analysis Method Equivalent to CFD based on Bit Operation,” *RIST News* No. 64, pp. 17-28, 2018.
- 14) Matsuoka: “Multiscale Emergence Analysis of Vertical Vortex Behavior based on Recurrent Bit Operation,” Exploratory Subject Study EX21204, 13th JHPCN Symposium, 2021.
- 15) Matsuoka: “Pursuit of an AI Surrogate Model for Time Evolution Computation in Fluid Analysis,” *SENAC* Vol. 55, No. 1, pp. 15-28, 2022.
- 16) Oki, Kikuchi, Matsuoka, Kikuchi, Itakura, Hirokawa, Nishikawa, Iwasawa, Asano, Saito, Ogata: “Development of a Non-thermal Fluid Simulation Code based on a Physical Model that Eliminates Artificial Hypotheses to the Extent Possible,” Program for Using the Earth Simulator for Industrial Strategies, pp. 89-99, FY 2014 Report on the Results of its Use, 2014.
- 17) Matsuoka, Mineo, Yokokawa, Takizuka, Igasaki, Watanabe, Itakura, Fukuda, Kikuchi, Kobayashi, Eagawa, Takemura, Kikuchi, Higasida, Aoyagi, Takami, Kobayashi: “Real-time Analysis of a Large-scale Computer Air Cooling Wind Field for the Realization of Measurement-fused Operation,” 11-MD05, JHPCN final report, May 2012.
- 18) Daniel H. Rothman: “Negative-Viscosity Lattice Gases”, *Journal of Statistical Physics*, Vol. 56, Nos. 3/4, 1989.
- 19) Rudy Raymond, Imamichi: “Cutting-edge Quantum Computer ‘IBM-Q’,” pp. 50-59, *ProVision* No. 92, 2017.
- 20) Matsuoka: “Fusion of a Lattice Gas Method Fluid Analysis Model with a Neural Network,” *SENAC* Vol. 54. No. 1, pp. 39-49, 2021.