Acceleration of Numerical Turbine using the Red–Black Method

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Background

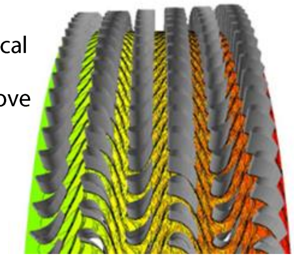
Numerical Turbine

- Steam turbines in thermal and nuclear power plants supply about 70% of the electricity in the world.
- Numerical Turbine is a program to simulate the physical state of the fluid around the turbine cascade [1].
- It is used to design efficient steam turbines and improve their maintainability.

Problem: Long execution time

- Expansion of the simulation scale of Numerical Turbine increases execution time.
- One of the time integration routines called "implicit" occupies about 35% of the total execution time.

→ It is needed to accelerate the implicit routine.



EX. droplet mass fraction distribution

Theoretical background of the implicit routine

- This routine calculates physical fields ΔQ^n of grid points derived from the vector of flux F_i, viscous term S, and source term H of the Navier-Stokes equation.

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial \boldsymbol{F}_i}{\partial \xi_i} + \boldsymbol{S} + \boldsymbol{H} = \boldsymbol{0} \quad (i = 1,2,3)$$

$$\Delta \boldsymbol{Q}^n = -\Delta t \left(\frac{\partial \boldsymbol{F}_i^n}{\partial \xi_i} + \boldsymbol{S}^n + \boldsymbol{H}^n \right)$$

- It is necessary to perform vector computing in the routine to exploit computational performance of modern high-performance computers.

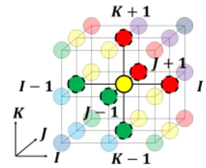
Calculation in the implicit routine

Data dependency of the implicit routine

- Calculating ΔQ^n of point (I, J, K) requires ΔQ^n of points $(I-1)$, $(J-1)$ and $(K-1)$ and ΔQ^{n-1} of points $(I+1)$, $(J+1)$ and $(K+1)$.
- Points being updated and their neighbors cannot be calculated at the same time.

Hyperplane method

- A group of grid points with the same color/number in the right figure is called a hyperplane [2].
- Adjacent points of the m-th hyperplane belong to the $m-1$-th and $m+1$-th ones.
- The grid points in one hyperplane can be updated at the same time.
- The hyperplane method allows vector calculations in the same hyperplane.



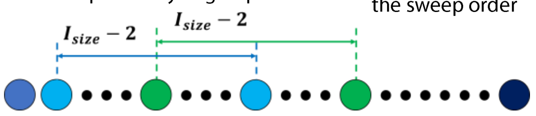
Data dependency of grid points

Hyperplane method and the sweep order

Bottleneck of the hyperplane method: Large stride memory accesses

- The vector calculations by the hyperplane method require stride memory accesses with a distance corresponding to the grid size.
- The stride memory accesses increase the number of loaded memory blocks.

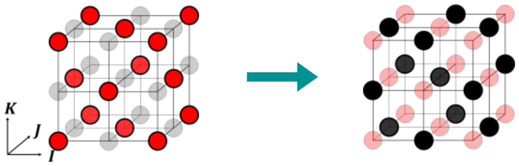
→ The memory access time becomes a bottleneck.



The stride distances among the same hyperplane points in the memory

Approach

Red-Black method



1st : Calculate all the red points referring ΔQ^{n-1} of black points

2nd : Calculate all the black points referring ΔQ^n of red points

- The colors of the neighboring points are different from each other.
- The Red-Black method avoids dependency among the adjacent points.
- The same color group can be updated at the same time.
- The calculations of the same color points can be vectorized.

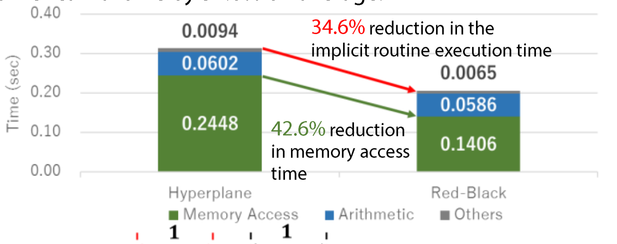
Memory access pattern

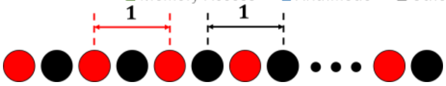
- The red and black points are arranged alternately in the memory, which performs unit stride accesses whose distances are 1.

→ The number of memory accesses can be reduced compared to the hyperplane method.

Evaluation

- We evaluate the implicit kernel with the hyperplane method and the Red-Black method using NEC SX-Aurora TSUBASA Vector Engine Type 10B.
- The Red-Black method can speedup the dominant routine of Numerical Turbine by 34.6% on average.





The unit stride distances among the same color points in the memory

Conclusions and future work

- We discuss applying the Red-Black method to the implicit routine to reduce the number of memory accesses.
- The Red-Black method can reduce the execution time of the implicit routine by 34.6% compared with that of the hyperplane method.
- Since the Red-Black method is not limited to conventional problem division, blocking for efficient use of cache is investigated.
- Further investigation is required for understanding the trade-off between performance and accuracy.

References

[1]S. Yamamoto et al., "Parallel computation of condensate flows through 2-d and 3-d multistage turbine cascades." In Proceeding International Gas Turbine Congress, 2007.

[2]H. Matsuoka et al., "Program optimization of Numerical Turbine for vector supercomputer SX-ACE." In Proceeding of Parallel CFD2016, p. 8, 2017.

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