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主　論　文　の　要　旨

論文題目　**Topology Optimization Method for Flow Channel Design Using Lattice Kinetic Scheme Considering Thermal and Unsteady Flows**
(格子運動論スキームを用いた、非定常流と熱伝導問題を考慮した流体流路のトポロジー最適化)

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論　文　内　容　の　要　旨

Structural optimization has become a significant design tool in a variety of physical fields since it is capable of obtaining optimal designs using numerical simulation techniques. Conventionally, structural design highly depend on engineering experience and the trial and error analysis, as a result, the design cost is high and optimal shapes are not always obtained. Therefore, structural optimization is attractive in many fields and numerous structural optimization methods have been developed, which can be classified into three types: size optimization, shape optimization and topology optimization. Size optimization changes the size, such as width, height of the object, and shape optimization changes the boundary but can not generate holes within the design area. Topology optimization method was first proposed by Bendsøe and Kikuchi in 1980's, which has the highest design flexibility since it allows the generating of holes and new boundaries within the design area, and not particularly depend on initial shape. Owing to these advantages, topology optimization has been applied to solve a variety of design problems of different physical fields.

Topology optimization is also attractive in fluid dynamics since the fluid devices' performance highly depend on the structures. The pioneering study of employing topology optimization method in solving fluid flow problems is by Borrvall and Petersson, who proposed a topology optimization method to minimize the power dissipation of Stokes flow. Since then the topology optimization methods have obtained widely applications in fluid dynamics. The finite element method has been commonly utilized to solve the Navier-Stokes equations in topology optimization regarding fluid flow due to it is a well-studied technique. However, the numerical accuracy of finite element method always depends on the mesh and the computational cost is high to solve the Navier-Stokes equations. And due to the computational cost of solving the governing equations of fluid, steady flows were primarily considered in previous researches.

The lattice Boltzmann method has become a promising numerical method of solving the Navier-Stokes equation due to its simple algorithm for easy implement of parallel computation. The lattice Boltzmann method is a scheme of kinetic theory, which models fluid medium at a microscopic level and uses a distribution function to calculate the dense of particles. The macroscopic quantities of fluid, such as velocity, pressure, and density can be calculated from the distribution functions. The lattice Boltzmann method restricts particles' velocity in some finite directions and its basic equation is the lattice Boltzmann equation, a space-discretized Boltzmann equation. Nevertheless, the lattice Boltzmann method requires a large amount of storage since it has to store the discrete distribution functions of every grid in the analysis domain. The requirement of memory is a key problem when a large-scale domain or three dimensional problems are treated in topology optimization for flow field problems.

In 2002, Inamuro proposed an extended lattice Boltzmann method, called the lattice kinetic scheme. The lattice kinetic scheme simplified the lattice Boltzmann method, as a result, the discrete distribution functions of all the grids with design domain are not stored in the computation, therefore, the lattice kinetic scheme can significantly save memory than the lattice Boltzmann method.

He and Luo proposed a new model lattice Boltzmann method, in which the density of fluid is treated as a constant to reduce the compressible effect. In this study, we combine this new lattice Boltzmann method and the kinetic scheme proposed by Inamuro, and obtain a new model of lattice kinetic scheme. This new scheme is adopted in topology optimization methods for fluid flows in this study.

This study aims at proposing topology optimization methods for channel design of incompressible viscous fluid flows using the lattice kinetic scheme. Also, we extend the topology optimization method for unsteady flow problems as well as unsteady flow and thermal coupled problems. We attempt to provide a structural design tool for fluid devices regarding complex flow conditions and provide a solution when the memory requirement is an issue in optimization for fluid flow.

Topology optimization is always treated as a problem of material distribution in the design domain and different optimization methods have been proposed to perform the optimization. In the study, the level-set method is adopted, which is one of the popular optimization method and it is grey-scale free. The level-set method employs a scalar function, called the level-set function, to express the material distribution in the design domain. The boundaries of materials can be explicitly extracted from the zero iso-surface of the level-set function. In accordance with the update of value's distribution of the level-set function, the shapes of boundaries are changed. In the standard level-set method, the level-set function is evolved by a Hamilton-Jacobi equation. However, this method of updating the level set function needs to reinitialize the level-set function to preserve the signed distance property in the process and it also may lead to numerical instability.

Yamada et al. proposed a method to update the level-set function using the gradient of an augmented objective functional and introduced the regularization term to control the geometry complexity. This method does not need to reinitialize the level-set function during the optimization and it has good numerical stability. A number of researches have employed this method in topology optimization for various problems, such as acoustics and fluid dynamics problems.

In the study, the method proposed by Yamada et al. is employed and the gradient of the objective functional is utilized as the design sensitivity to update the level set function. The adjoint functions and design sensitivity are derived via the adjoint method, which is efficient in obtaining the variations of a function.

As a first step of the study, the topology optimization method is applied to flow channel design of steady flow. The validity of the derived design sensitivity is verified by comparing its values with the finite difference approximation of the objective functional. Numerical examples are presented to compare the optimized results with those obtained in previous researches as well as those obtained by lattice Boltzmann method -based method. The numerical examples confirm that the proposed method can obtain valid optimization shape and can significantly reduce memory usage compared to lattice Boltzmann method based method.

Then the topology optimization method is applied to design flow channel considering unsteady flows. The design sensitivity and adjoint function are derived in the same approach as that used in topology optimization for steady flows. Through comparing the optimization results with those obtained in previous researches, the effectiveness of the proposed method is demonstrated. In addition, the application of the proposed method to maximize the dissipation kinetic energy can provide a tool to design hydraulic anti-vibration devices, such as damper.

Finally, we develop a topology optimization method for unsteady fluid flow and thermal coupled problems. Both temperature field and fluid flow field are computed using the lattice kinetic scheme. Adjoint functions and design sensitivity are derived based on the lattice kinetic scheme for two fields. Numerical examples of maximization of average temperature and heat exchange are implemented. The proposed method is able to solve shape design problems regarding unsteady fluid flow coupled with thermal.