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LATTICE-BOLTZMAN METHOD IN CFD MODELLING OF DIRECT ACTING RELIEF VALVE

MODELOWANIE CFD ZAWORU PRZELEWOWEGO BEZPOŚREDNIEGO DZIAŁANIA Z ZASTOSOWANIEM METODY SIATKOWEJ BOLTZMANA (LBM)

A b s t r a c t

This paper presents the modelling of a direct acting relief valve with the use of the new approach of CFD techniques which uses the Lattice Boltzman Method (LBM). It allows for eliminating the biggest problem that occurs during the simulation of a valve operation, which is the motion of a working component. During traditional CFD modeling, a deformed mesh has to be used in such a case, which may lead to the occurrence of computational cells with negative volume and, as a consequence, remeshing of fluid domain.

Keywords: LBM, CFD, FSI, direct acting relief valve

S t r e s z c z e n i e

W artykule przedstawiono zastosowanie metody symulacji numerycznych przepływu wykorzystującą metodę siatkową Boltzmana (LBM) w modelowaniu zaworu przelewowego bezpośredniego działania. Umożliwia ona wyeliminowanie największego problemu, jaki występuje podczas symulacji pracy zaworu przelewowego tradycyjnymi metodami CFD, którą jest konieczność wykorzystywania deformującej się siatki modelu dyskretnego.

Słowa kluczowe: LBM, CFD, FSI, zawór przelewowy bezpośredniego działania

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1. Introduction

Modelling of fluid power components at working conditions is a challenge, even by means of sophisticated simulation tools like computational fluid dynamics (CFD). A direct relief valve, which has a relatively simple structure, may cause a lot of modelling problems. In the simplest case, it consists of a lift component (cone or sphere) and spring whose rate and initial deflection determine the opening pressure and valve characteristic. Despite the significant development of CFD method and its possibilities in fluid-structure interaction (FSI) simulations, which includes mesh deformations, which may lead to the occurrence of distorted cells with negative volume [1, 2]. A solution may be the use of automating remeshing procedure, however, it requires much more computational time and resources. A new approach of FSI named Immersed Solids, which was presented during the modelling of the relief valve in [2], does not use grid deformations. Solid objects occupy the same volume as the fluid domain, which contains this object. However, such an approach does not allow for capturing flow forces accurately enough. Previous research [2] has shown that flow forces that arise on lift components differ from those obtained from the traditional CFD modelling. The flow forces, which appear during a valve operation have essential meaning for the modelling of a relief valve and therefore an efficient way of simulation valves in working conditions is still requested. A new quality in modelling FSI of hydraulic valves may give a new approach of numerical flow simulation based on the Lattice Boltzman Method (LBM).

2. Lattice Boltzman Method approach in fluid flow

The Lattice Boltzman Method (LBM) is a particle-based method, which is an improved modification of Lattice Gas Automata. Recently, LBM becomes more and more popular as an alternative to the conventional FEM or FVM based CFD approaches. A direct connection of LBM with the kinetic theory of gases may be adopted particularly for fluid-structure interaction simulations. LBM uses a spatial discretization method named lattice which consists of discrete points with a discrete set of velocity directions located in the Cartesian

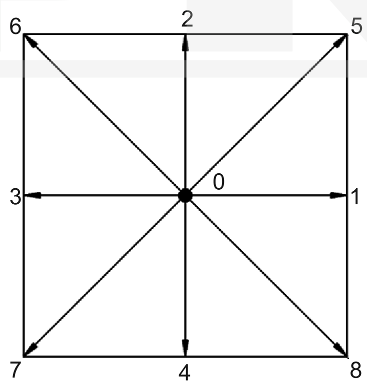

Fig. 1. D2Q9 lattice

space. The set of velocities uses a common terminology which describes the dimension problem and a number of velocity vectors: D_nQ_m, where n stands for dimension, while m for velocity directions. An example of two dimensional lattice is presented in Fig. 1.

There are many approaches of LBM, but all of them have a common feature which is time stepping model based on the propagate-collide scheme. The Boltzman equation for continuum space with discrete velocities can be presented as [3]:

$$\frac{\partial f_i}{\partial t} + \mathbf{e}_i \cdot \Delta f_i = \Omega_i, \quad i = 1,\ldots,b \tag{1}$$

where:

Ω_i – is the collision operator,
$\mathbf{e}_i$ – is a set of discrete velocities,
b – is a number of velocities directions, $b = 4$ for a two dimensional lattice,
f_i – is the probability distribution function.

If we assume $\Omega_i = 0$ the Eq. 1. Is discretized on the lattice in the following way:

$$f_i(\mathbf{r} + \mathbf{e}_i, t + dt) = f_i(\mathbf{r}, t) + \Omega_i(f_1, \ldots, f_b), \quad i = 1,\ldots,b \tag{2}$$

The density and momentum can be derived from the following equations:

$$\rho = \sum_{i=1}^{b} f_i \tag{3}$$

$$\rho\mathbf{v} = \sum_{i=1}^{b} f_i \mathbf{e}_i \tag{4}$$

The collision operator Ω_i is modelled as a relaxation of the probability distribution function towards an equilibrium state. One of the most common approaches uses single relaxation time based on the Bhatnagar-Gross-Krook approximation [3]:

$$\Omega_i = \frac{1}{\tau}(f_i^{eq} - f_i) \tag{5}$$

where:

τ – is relaxation time,
f_i^{eq} – is the local equilibrium function.

The local equilibrium function f_i^{eq} is derived directly from the Maxwell-Boltzman distribution with the same macroscopic variables of the pre-collision state satisfying mass and momentum conservation and can be expressed as follows [3]:

$$f_i^{eq} = \rho w_i \left(1 + \frac{e_{i\alpha} u_\alpha}{c_s^2} + \frac{u_\alpha u_\beta}{2c_s^2} \left(\frac{e_{i\alpha} e_{i\beta}}{c_s^2} - \delta_{\alpha\beta} \right) \right) \tag{6}$$

where:

u – is macroscopic velocity,
δ – is the Kronecker symbol,
w_i – is weighting constant,
α, β – spacial components of vectors appearing in the equation,

3. Object of study

The direct acting relief valve with a cone shape lift element presented schematically on Fig. 2 is the object of the study.

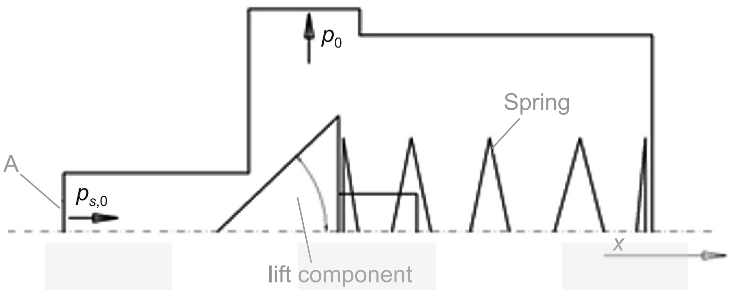

Fig. 2. A scheme of direct acting relief valve

The main aim of the relief valve is to secure the hydraulic system against excessive rise of pressure. When the pressure at the hydraulic line rises (port A) and exceeds the value of valve opening (p_s), the spring yields and the lift element releases working fluid to the tank. The position of lift element depends on forces acting on it, where the flow forces are the most difficult to evaluate. Additionally, due to the lack of damping element, during the operation the lift element may oscillate until the equilibrium state is found.

4. FSI simulation using LBM

The Lattice Boltzman Method is a relatively new approach of flow simulations and is still under development, while traditional CFD approaches using the finite element method (FEM) or the finite volume method (FVM) have existed for decades. One of the commercial LBM applications was implemented in XFlow CFD code. A model of relief valve presented in Fig. 2. was used in XFlow to create a lattice for numerical calculations (Fig. 3.).

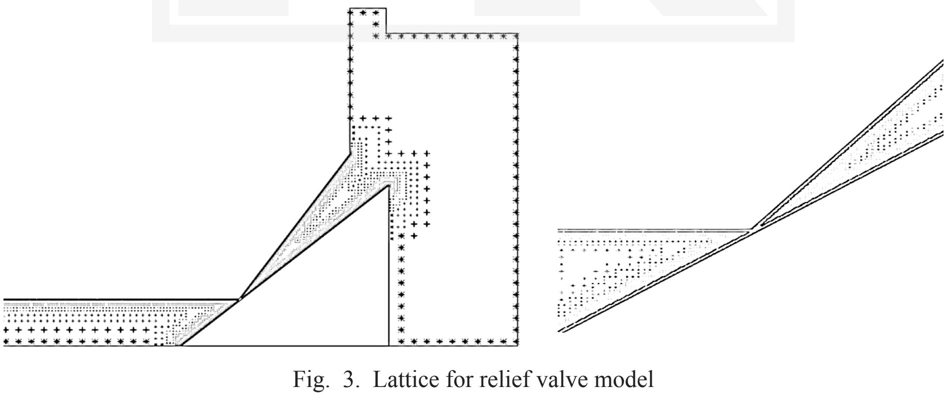

Fig. 3. Lattice for relief valve model

The created lattice is not uniform at the fluid domain, in the area of valve seat and lift element the distance between lattice nodes are much smaller to allow for the described accurate flow at the gap between the lift component and valve seat. The huge advantage of the LBM approach is no necessity of creating a grid, which allows for creating one model for simulation for various flow conditions. Another advantage of LBM is the possibility of rigid body simulation with interaction between valve components (collisions) as well. In the case of the presented relief valve it gives the possibility of simulation condition when the valve is opened and a sudden drop of pressure in the hydraulic line occurs. It leads to a situation when the lift component due to the spring force may hit at the valve seat and then reflect. The results of such conditions were shown in Fig. 4. At initially opened valve (pressure at the hydraulic line $p > p_s$) suddenly pressure drops below the value of opening. The response of the valve is presented in the lower plot in Fig. 4.

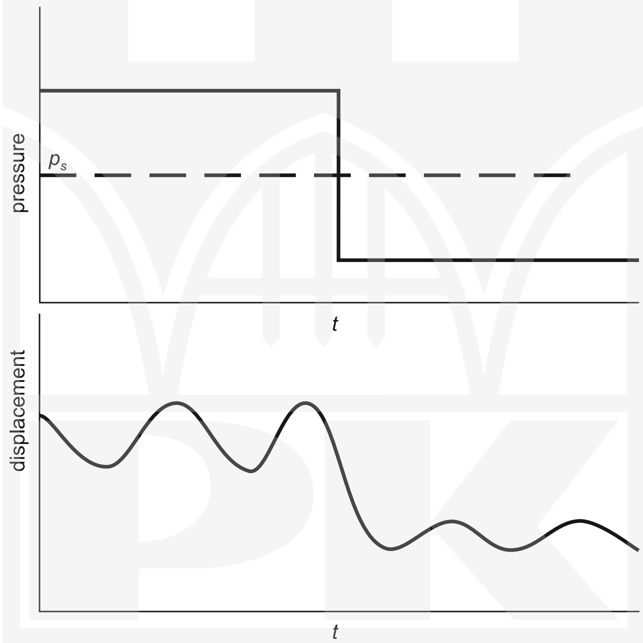

Fig. 4. Pressure in the hydraulic line (upper plot) and the displacement of lift element (lower plot)

The position of the lift element of relief valve was obtained at one model without any modifications and necessity of generating various lattice nodes for different positions of the lift element. The presented results were obtained for 2D model, which does not exactly describe the valve presented in Fig. 2, therefore the results presented in Fig. 4 do not include units. The aim of the conducted simulations was to verify possibilities of the LBM method in a relatively short time in modelling dynamics of the relief valve.

The presented results were obtained for a model which includes interaction between the valve seat and lift element. They were treated as rigid bodies with the ideal elastic model of collision.

5. Conclusions

This paper presents an attempt to use the LBM method for simulation dynamics of a direct acting relief valve. For such purpose, a commercial CFD code named XFlow was used. The created model was used for the investigations of the relief valve during a sudden drop of pressure in the hydraulic line below the value in which the valve is opening. Numerical simulations allowed for obtaining a response of valve components on such conditions, as the displacement of lift element. The application of the LBM method also allowed for simulation valve dynamics, taking into account phenomena like collision between the lift element and valve seat.

LBM seems to be a very promising tool in modelling dynamics of hydraulic valves, which allows for investigating not only flow phenomena during fluid flow but also interaction between valve components. It breaks the limits in simulation of dynamic system during fluid flow and gives much wider possibilities than the traditional approach of CFD tools based on the FEM or FVM. The only disadvantage is that the lattice nodes have to be created in a proper way close to the boundary with complex geometry.

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