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GAS FLOW IN A MICRO-CHANNEL WITH AN ELASTIC OBSTACLE

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KEY WORDS

fluid-structure interaction (FSI**)**, rarefied gas, DSMC, Euler-Bernoulli beam, synchronization of the codes, frequency response functions

ABSTRACT

1.Introduction

The analyses of gas flow at microscale level are important tasks for many high technological devices and they are subjects of studies of many researchers. The essential and intriguing element is that there are fundamental differences in the microfluidic considerations with respect to those of conventional flows at macroscales scales. In many cases in micro channels, where the gas flows, there are obstacles with different shapes. In most of the cases they are considered as rigid bodies. The proper model of such system requires considering the deformability of the obstacle. The consideration of the elastic properties of the obstacle means that it will deform due to the gas flow and due to its motion the gas flow will be disturbed.
For model description of MEMS, the number of Knudsen Kn (the ratio of mean free path of molecules to specific geometrical dimension) is a key dimensionless parameter. In such a devices, the Knudsen number at standard temperature and pressure is large due to the small characteristic size that is comparable to molecular mean free path.
Up to our knowledge, there are no studies available about a gas flow in microchannel simulated by the direct simulation Monte Carlo (DSMC) method interacting with an elastic obstacle.

2. Problem formulation

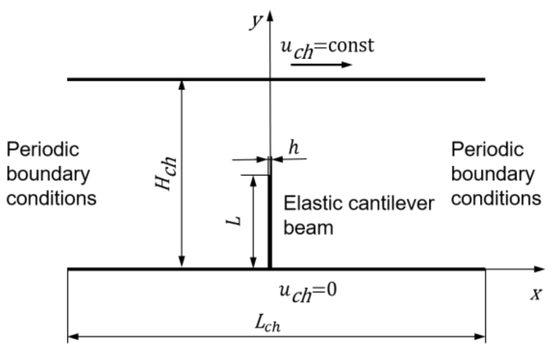


Figure 1. A geometrical scheme of the problem

Fig. 1 presents schematically the considered in this work problem. Two-dimensional Couette rarefied gas flow which interacts with an obstacle is considered. The obstacle is an elastic beam fixed to the bottom wall. The bottom wall is at rest while the top is moving with constant velocity. Placing an elastic beam in the channel turns the problem it into a complex highly non-linear one.
The gas behaviour is studied by the DSMC method using the high effective Simplified Bernoulli trial approach [1]. Boundary conditions of fully diffuse reflection of gas molecules are imposed on the walls of the channel and cantilever. A Cartesian uniform mesh in the computational domain as a basic mesh is used. In cells of a basic mesh, was used the Transient Adaptive Sub-cells (TAS) technique [22] to improve the DSMC spatial accuracy. An adaptive unstructured mesh in a tiny area near the elastic beam is used.
The beam was modelled by the geometrically nonlinear Euler-Bernouli beam theory. A reduced model based on the three modes reduction was used in order to speed up the calculations.
DSMC algorithm was coupled with a computer code simulating the geometrically nonlinear vibration of a clamped elastic beam in order to calculate a coupled problem of fluid-structure interaction
At each time step the difference between the calculated pressure of the front and back side of the beam is applied as a loading of the beam and its vibration is calculated. The influence of the beam on the gas flow is considered by re-meshing the DSMC mesh and correcting the velocity of every reflected particle from the wall by adding velocity of the beam boundary node, which is closest to the point of particle impact.

3. Results

For the numerical calculations the following the geometric and physical parameters were used: the height of the channel is H_{ch}=4.58×10-6[m], the channel length is L_{ch}=4.58×10-5[m], the length of the beam is L=2.49×10-6[m] , h=0.01L, b=2h, Young modulus of the beam material was E=1.128 Mpa, density ρ=8960 kg/m^3 . The character length used in the calculations of the gas flow is equal to the elastic beam length. In this primordial study, the Knudsen number was kept fixed to 0.05. Numerical examples with five different velocities of the flow were considered - corresponding to Mach numbers M=0.2, 0.4, 0.8, 1.6, and 3.2.
DSMC basic Cartesian uniform mesh was 400×80 cells with a total number of 3.6×105 particles. We tested DSMC with four times more particles and a corresponding finer mesh. The results showed that the frequencies of the responses of the beam calculated with different numbers of particles were practically indistinguishable even for low Mach numbers.
Figures 2 shows rarefied gas flow along the channel, interacting with the deformable beam for Mach number 3.2 after the transition period.
The left parts of the figures show the main macroscopic gas properties obtained by DSMC: horizontal velocity, the vertical velocity, the pressure, and the temperature fields, from top to bottom. Elastic beam disturbs Couette flow. At Mach number 0.4 it disturbs mainly horizontal velocity field, while for Mach number 3.2 disturbances are significant in all presented macroscopic properties of the fluid. Pressure in front of the beam increases while the pressure behind the beam decreases significantly. In this way, an under-pressure region behind the beam is formed and it reaches the top channel wall. The deformed cantilever is shown on the right side. The geometry calculated according to DSMC is plotted in blue colour, while the red line displays the elastic beam position computed according to the Cantilever code. One can see an excellent agreement between geometries in both codes. After a transition period, the elastic beam vibrates with very small amplitudes (around 1×10^{-8} to 3×10^{-8}, depending on the flow velocity) around a new equilibrium state (bended).
The response of the beam during its interaction with the gas at M=1.6 is presented in Fig. 3 a, b. The stochastic nature of the DSMC and the way of the consideration of the interaction between the gas particles and the beam lead to a stochastic character of the loading. Similar are the diagrams for M=0.2, 0.4, 0.8 and M=3.2 (not shown here).
One can see that in spite of the chaotic character of the loading three frequencies that dominate the response of the beam can be outlined. They are much smaller than the natural frequencies and the values of these frequencies decrease with the increasing of the Mach number. It must be noted, however, that the decreasing of the response frequencies is the same for the first, second and third frequencies. In Fig. 4 are plotted the curves for the first, second and third frequencies of the response depending on the Mach number normalized,

correspondingly, by the first, second and third natural frequencies of the beam. It turned out that the curves for these three different frequencies coincide. This means that the gas load influences included in the response of the beam all three frequencies in an equal degree. Another conclusion that can be invoked is that the frequencies of the response could be used for estimating the velocity of the gas flow.

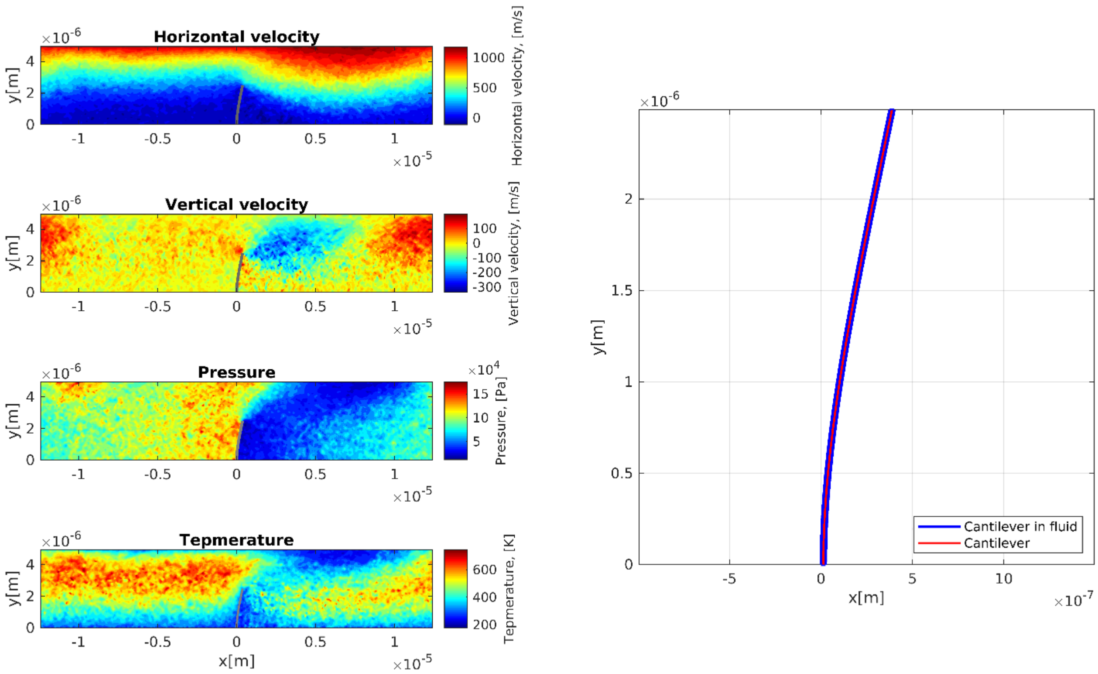
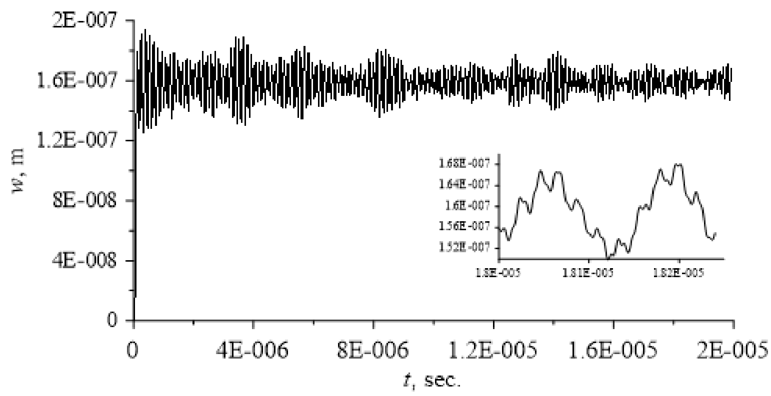
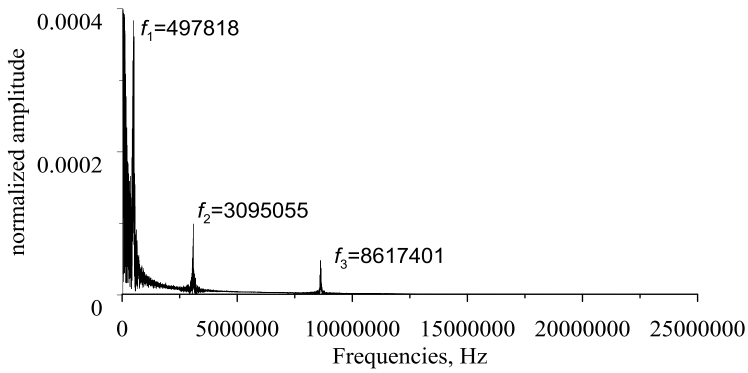


Figure 2. Horizontal velocity, vertical velocity, pressure, and temperature fields, from top to bottom (left part) and deflections along beam length (right part) for M=3.2.



(a)



(b)

Figure 3 a-b. The time-history diagram (a) and frequency-response functions at the top of the beam for M=1.6

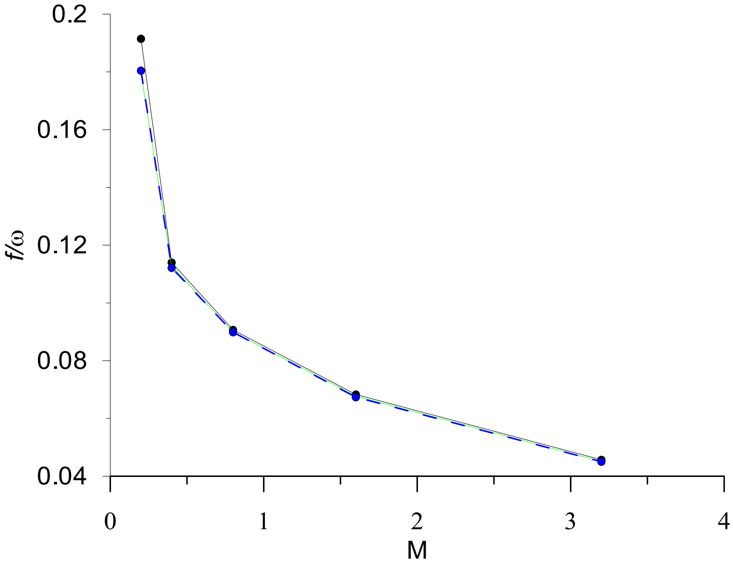


Figure 4. Influence of the gas velocity (Mach number) on the normalized frequencies f_i/ω_1 .of the response. Black colour - first frequency, dashed blue colour – second frequency. Green colour – third frequency.

4. Conclusions

The main conclusion of the present research is that the velocity of the flow could influence essentially the cantilever behavior and this effect could be used to study important phenomena in many high technological devices. From the other side, the elastic motion of the beam disturbs the gas flow and lead to complicated behavior of the gas particles. It is important to note that the decreasing of the frequencies of the response is stronger for low Mach numbers. The fact that the frequency of the oscillation is the most sensitive for low speeds of the gas flow makes the potential sensors suitable for many applications. If the obstacle has a piezo-electric properties the developed model of fluid structure interaction can be used to detect or measure gas flows in micro channels.

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