Vibrations of an elastic body under the influence of rarefied gas flow

Institute of Mechanics - BAS

Kiril Shterev and Emil Manoach

Outline

- Motivation
- Objectives
- Methods:
  - Large amplitude vibrations of the beam
  - DSMC (molecular approach)
- Problem formulation and results
  - Unsteady flow past a flat plate normal to the fluid flow
  - Study the dynamic behavior of an elastic beam interacting with a gas flow when the first natural frequency of the beam is close and equal to vortex-induced vibrations of the gas flow
- Conclusions

Motivation

- FSI – key for resolving many physical problems that cannot be handled separately from a structural or fluid point of view – (see the works of Paidoussis group);
- To study FSI at a micro-level: dimensions from 1mm to 1μm;
- Fundamental differences in the microfluidic considerations with respect to those of conventional flows at macroscales;
- The problems of gas flow at microscale have great importance for many high technological devices and they are subjects in studies of many researchers;

Examples of applications:

- Micro-Electro-Mechanical Systems (MEMS);
- The tip of Scanning Electron Microscope (SEM);
- Energy Harvesting Micro-Electro-Mechanical Systems (EH-MEMS);
- MEMS in a boundary layer of a fluid flow;

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Objectives

- Develop appropriate software (Usually fluid flow is considered by adding additional forces (added inertia, gravity forces, viscose friction, etc.) to the equations of motion of the structure);
- Develop an interface between the codes modeling the gas flow (DSMC) and the oscillations of the elastic element;
- Direct Simulation Monte-Carlo (DSMC) is a molecular approach used to model gas flow;
- Up to our knowledge, there are no studies of gas flows (rarefied gas) interacting with an elastic obstacle(s) that uses DSMC (molecular approach to model gas)!
- To perform a parametric study of the dynamic behavior (oscillations) of elastic elements subjected to rarefied gas flow to find the maximal amplitudes of the beam vibrations;

Methods: Geometrically nonlinear Euler-Bernoulli beam

The equations of motion of the beam, which consider large displacements, can be presented by the following equation (Meirovitch, L., Fundamentals of Vibrations. 2001: McGraw-Hill.)

$$\frac{\partial N}{\partial y}+\rho A\frac{\partial^2 u}{\partial t^2}=0$$

$$\frac{\partial^2 M}{\partial y^2}+c_d\frac{\partial w}{\partial t}+N\frac{\partial^2 w}{\partial y^2}+\rho A\frac{\partial^2 w}{\partial t^2}=p(y,t) \qquad 0<y<L$$

Dimensionless variables

$$\bar{y}=y/L, \quad \bar{w}=w/L, \quad \bar{t}=tc/L, \quad c=\sqrt{E/\rho}$$

After transformation and simplification, the equations of motion of the beam can be transformed in

$$\frac{\partial^4 \bar{w}}{\partial \bar{y}^4}+c_v\frac{\partial \bar{w}}{\partial \bar{t}}+\alpha^{-1}\frac{\partial^2 \bar{w}}{\partial \bar{t}^2}=p_1+\bar{G}_l(y,t),$$

$$p_1=\frac{p(\bar{y},t)L^3}{EI}, \quad \bar{G}_L=\frac{1}{2}\left(\int_0^1\left(\frac{\partial \bar{w}}{\partial \xi}\right)^2 d\xi\right)\frac{\partial^2 \bar{w}}{\partial \bar{y}^2}, \alpha=\frac{12L^2}{h^2}$$

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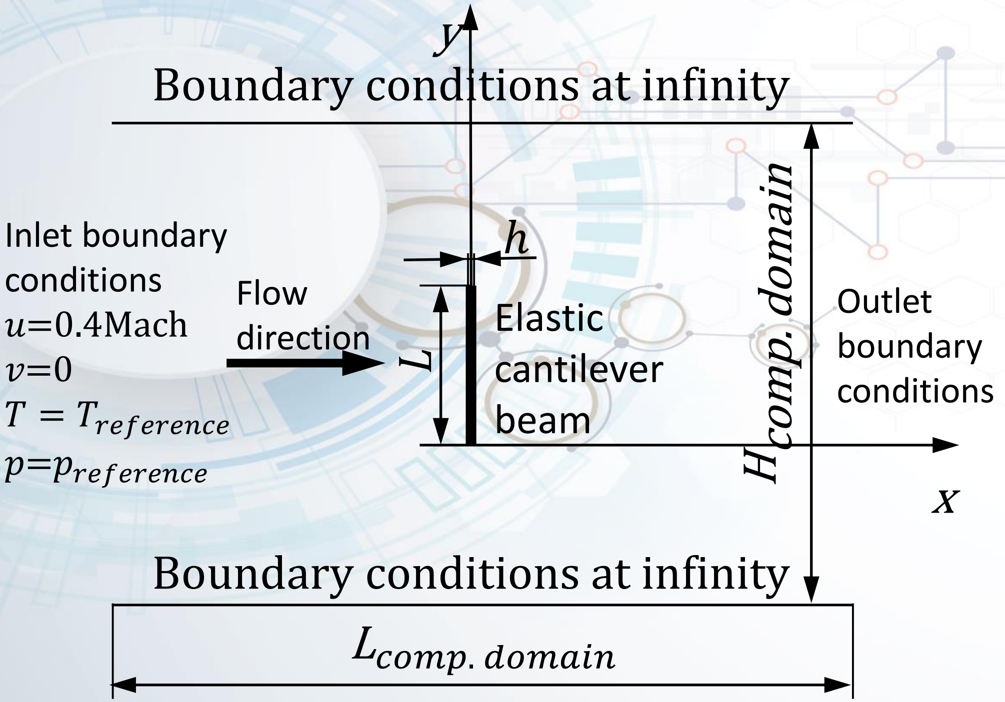
Methods: DSMC (molecular approach)

- DSMC collision scheme is the so-called Stefanov's Simplified Bernoulli trials (SBT) (Stefanov, 2011);
- Transient Adaptive Sub-cells (TAS) technique (Bird, 2003) was used for the local mesh refinement;
- Fallow Shterev’s recommendations of application of SBT (K. Shterev 2021);
- DSMC preliminary results were obtained on basic mesh with 1200x400 cells and 8.6 million particles;

Problem formulation

- Parametric study of the problem of the oscillations of a beam subjected to Vortex-Induced Vibrations (VIV). The problem corresponds to the flow past a flat plate normal to the fluid flow. It is a standard problem in fluid mechanics when the plate is rigid;



Select flow parameters:

- **Knudsen (Kn=λ/L) and Mach numbers have to be appropriately selected!**
- Smaller Kn number tends to continuum flow, **the fluid flow is unsteady (that gives us a possibility to study VIV)** but **increases the DSMC computational time;**
- Mach number should NOT be in or close to a transition regime!
- Based on a Shterev and Stefanov (K. Shterev and S. Stefanov 2017) study of microflow regimes and our calculations for this case, we selected **Kn=0.014 and Mach=0.4;**
- The length of the cantilever is **L= 8.886μm;**

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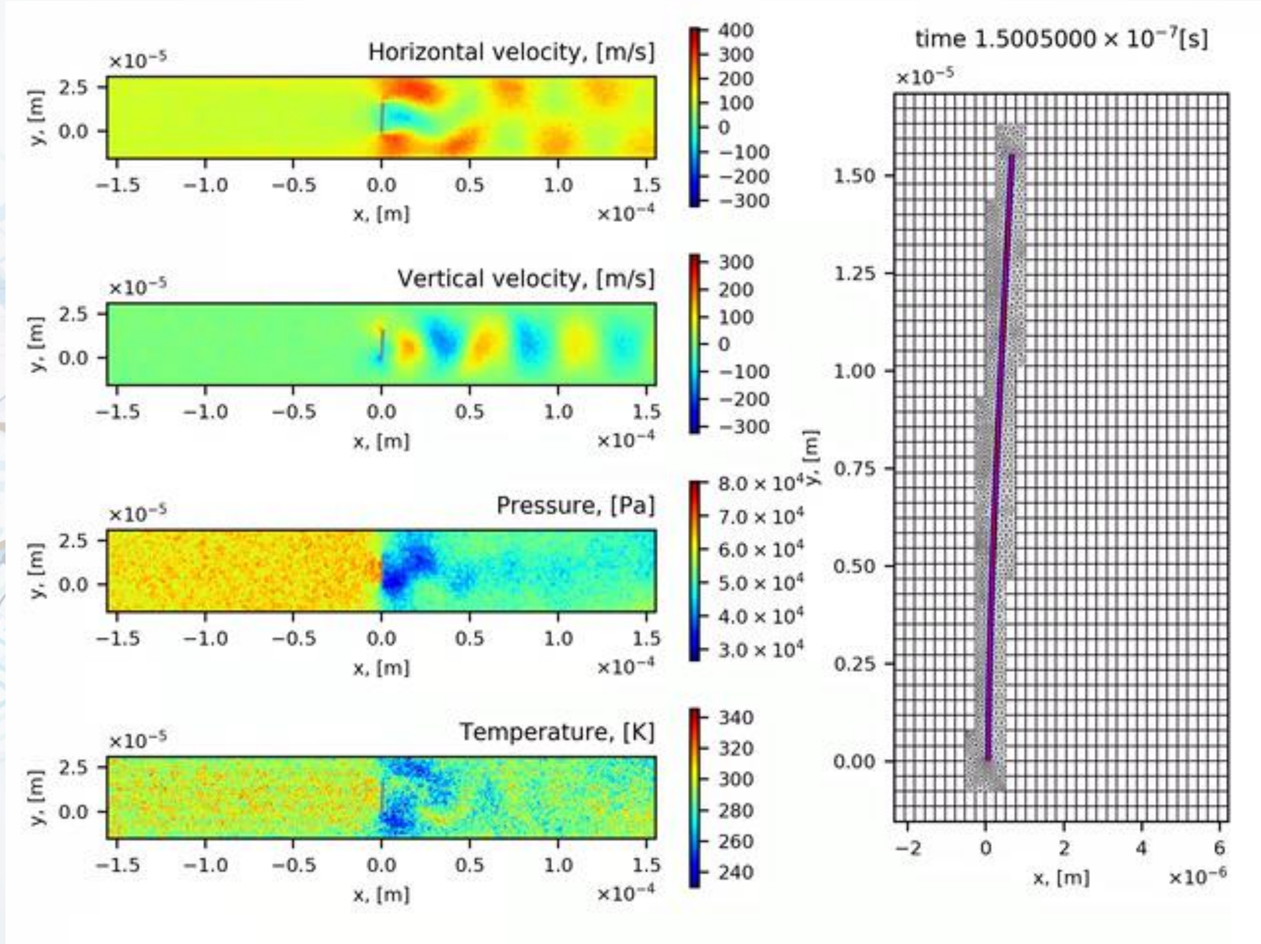
The flow past cantilever at Mach=0.4 with Karman vortex street



We selected the following parameters:

After preliminary parameters' variations:

- We selected the material of the elastic beam to be Tungsten carbide (WC) with Young's modulus 550[Gpa] and density 15.8[g/m^3];
- **We selected to fix Mach and Knudsen numbers and to vary the thickness of the elastic beam;**
- The frequency of VIV is 2.695[MHz];
- The first natural frequency of the elastic beam calculated according to the Euler-Bernoulli beam theory is equal to the frequency of VIV when the thickness of the elastic beam is equal to **0.021993xL=0.195μm;**
- **So, according to the preliminary calculations, we expect the elastic beam with a thickness of 0.195μm to oscillate with maximum amplitude compared to elastic beams with other thicknesses;**

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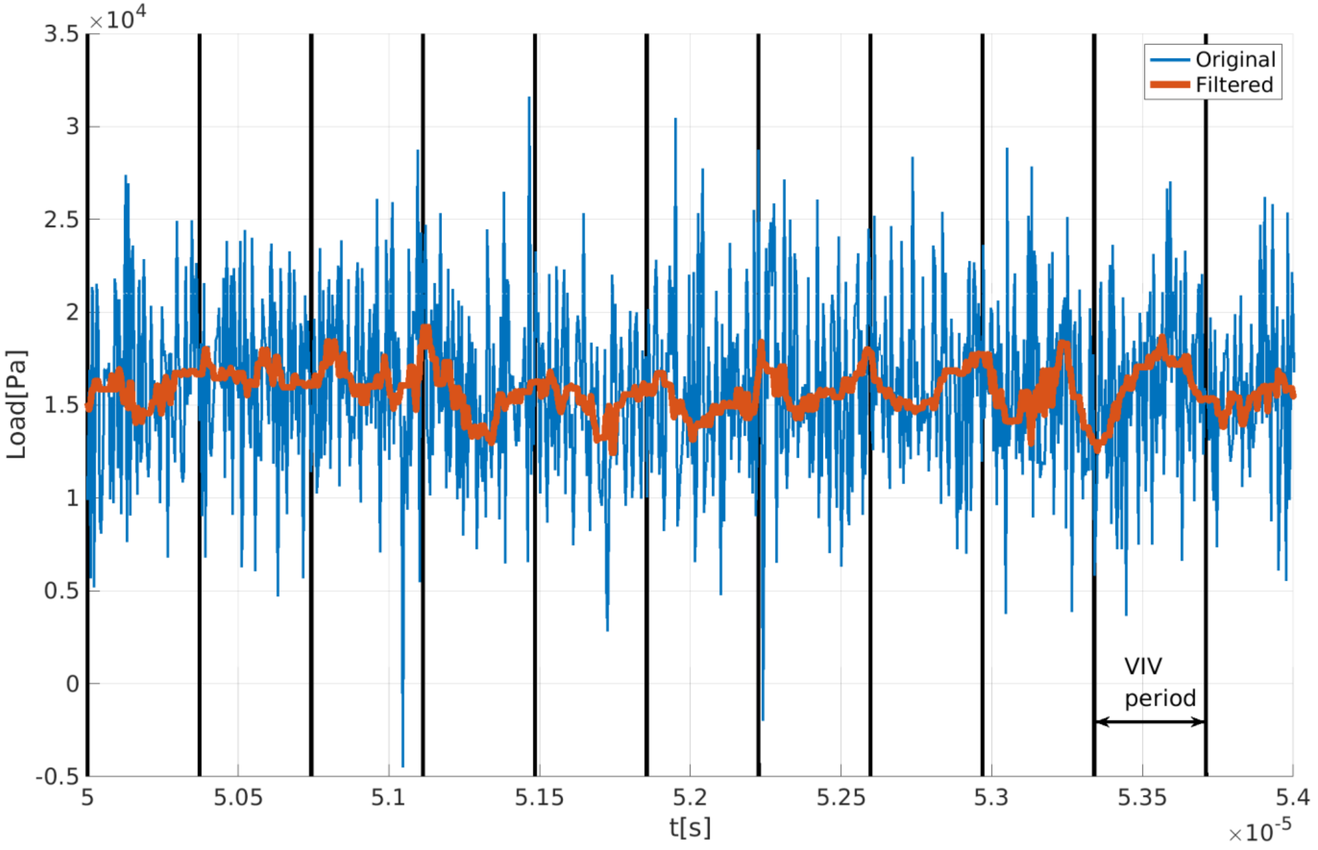
Results

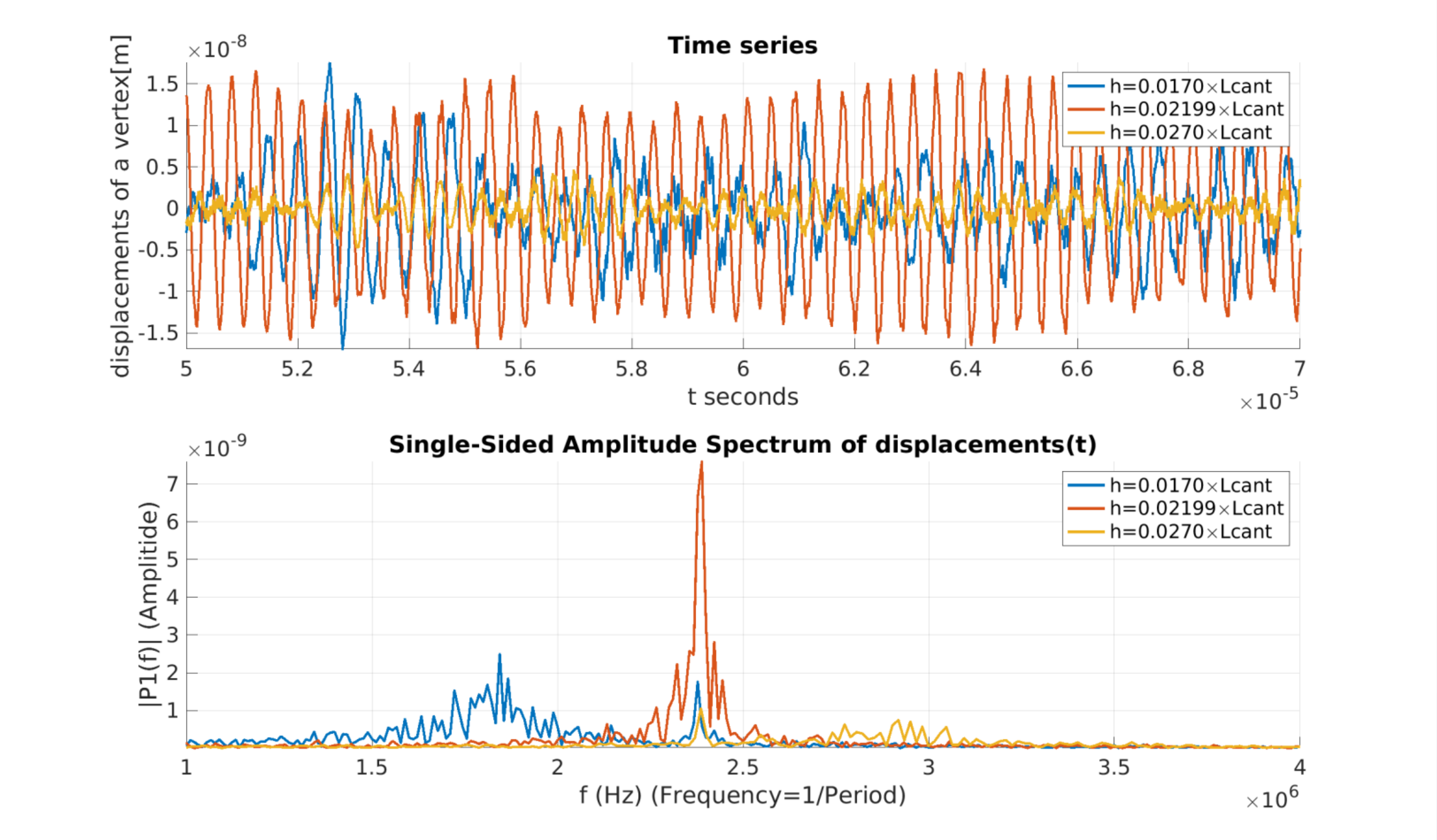
A load of one finite element on an elastic beam close to the top

- The load is stochastic (microscopic load);
- You can see also the periods of VIV (macroscopic load) of filtered load;



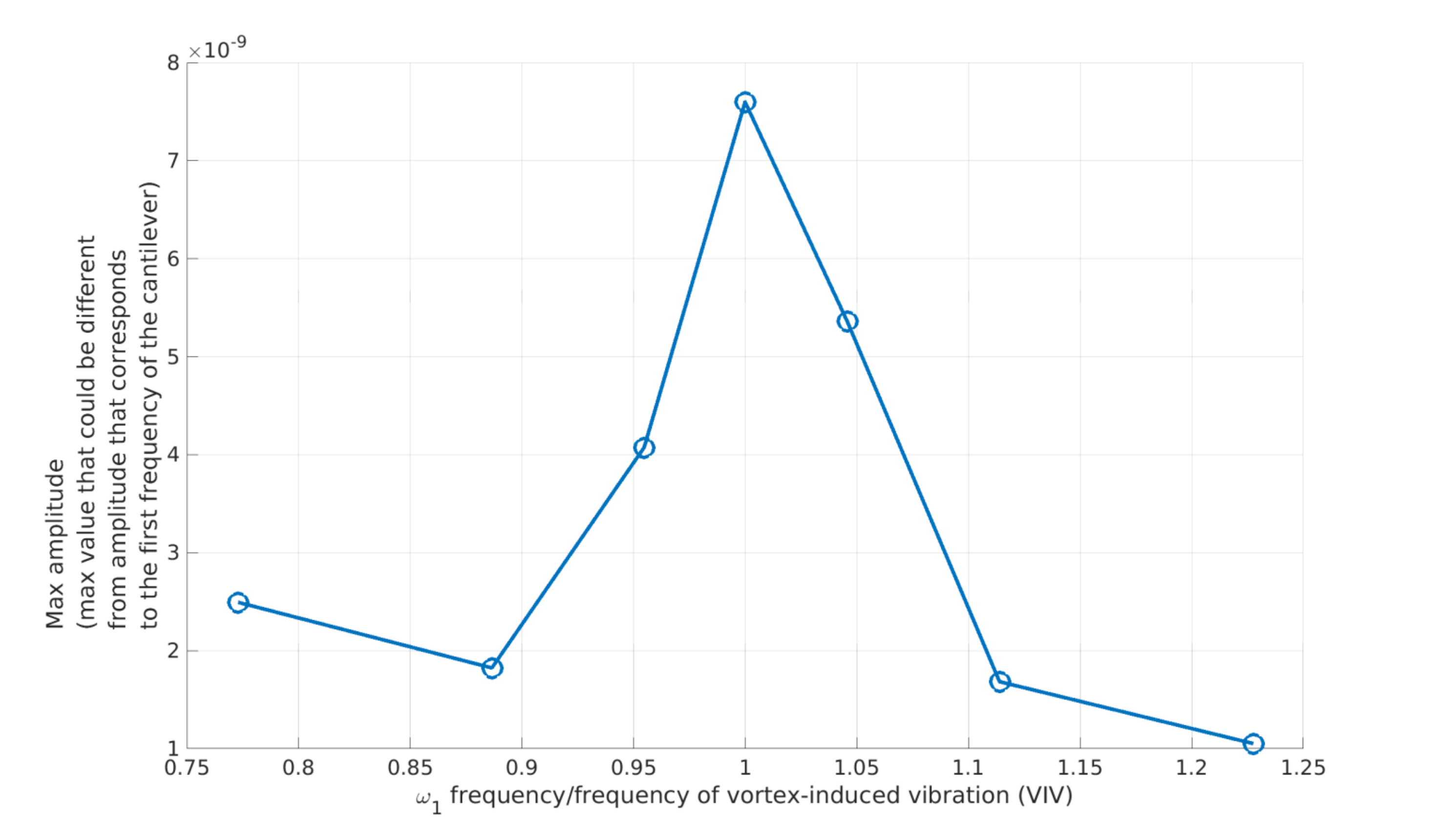
Results

Displacements of the tip of the elastic beam (top part) and single-sided amplitude spectrum, FFT (bottom part)



Results

Max amplitude as a function of the normalized first frequency of the elastic beam using the frequency of the VIV



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Conclusions

- A hybrid method was developed to study the fluid-structure interactions and the influence of the gas flow on the vibration of an elastic beam;
- The variation of the thickness and the vibrations of the elastic beam have negligible influence on the gas flow tending to zero;
- It is shown that the proper selection of the mechanical parameters of the beam the amplitude of vibrations could be maximized – application in sensors, actuators, and energy-harvesting devices;

Thank You!

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