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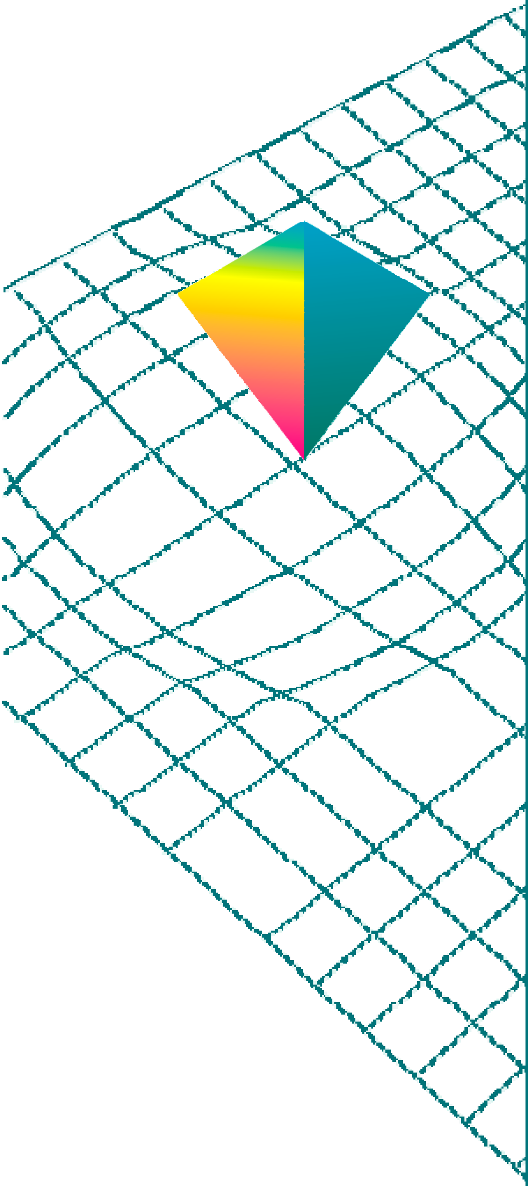

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50. Internationales Wissenschaftliches Kolloquium
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Miloš Miloševic, Života Živkovic, Jörg Burgold, Helmut Wurmus

Modeling Of Coupled Fluid-Structure Integration At A High Resolution Microstructured Cantilever Sensor For Fluid Flow Velocities Measuring

ABSTRACT

The essential necessity for developing new types of multiphysical microdevices lies in the fact of exact understanding of complex interactions between thermal, mechanical, electrical, magnetical and/or fluidic fields as physical phenomena that occur in them. So, to make a approach view it is necessary to understand the coupled effects of these phenomena, not only their independent influences. For that, it is imperative to use coupled-field analyses that take into account mutual interactions of two or more different disciplines of engineering. In this paper fluid-solid interaction problems will be presented in an example of a fluid-structural analysis of an interaction between a fluid and a structure at a high resolution silicon microstructured cantilever sensor that is used for measuring flow velocities of liquids especially in turbulence regimes by transforming effects of fluid flow velocities into extreme small deflections of a cantilever. For that purposes a sequential weak coupling algorithm of a 3D coupled-field analysis of the simulation software ANSYS will be utilized.

1. INTRODUCTION

Agile progresses in development of microsystems technologies and in developing new, complex microdevices are mainly enabled by modern concepts of designing and modeling new devices that substitute the traditional way based on experimental investigations that involved several design and fabrication cycles until the optimal specifications were satisfied. That new concept is based on Computer Aided Design (CAD) with different numerical simulation tools basically established on Finite Element Analysis (FEA) that are an essential key for designing and manufacturing micromechatronical systems with higher performance and reliability, reduced costs, shorter development cycles and time-saving approach.

All micromechatronical systems base their function on some kind of interactions between thermal, mechanical, electrical, magnetic or fluidic fields for performing their complex functions. So, it is not enough to understand these areas individually, but the coupled effects of these phenomena at the same time. For that purpose CAD with numerical simulation tools have been developed to model and simulate microsystems including interactions between different physical fields by coupled-field analyses.

A coupled-field analysis is an analysis that takes into account the interaction between two or more different disciplines of engineering. For example, a piezoelectric analysis at a piezoelectric actuator handles the interaction between structural and electric fields. Other examples of coupled-field analyses are thermal-stress analyses for bimetallic actuators, magneto-structural analyses for electromagnetic actuators and fluid-structure analyses for fluid flow considerations.

2. FLUID-STRUCTURE COUPLED FIELD ANALYSIS

A fluid-structure analysis that is based on coupled fluid-solid interactions considers caused displacements of an elastic solid material caused by fluid flow or fluid flow disturbance that is caused by a solid obstacle. For this purposes nonlinear transient Fluid-Structure Interaction (FSI) is the coupled-field problem that must be taken into account. This is necessary because transfer of fluid forces from the fluid to the structure and displacements and velocities from the structure to the fluid occurs simultaneously across the fluid-solid interface. In that case for the modeling purposes the fluid-solid sequential weak coupling algorithm is predicted in simulation software ANSYS. It provides the fluid-solid interaction between finite elements in the fluid and structural region. Fig. 1 shows the algorithm of the fluid-solid sequential weak coupling analysis. From the algorithm it can be seen that the equations for the fluid and solid domains are solved sequentially and fluid forces and heat fluxes and solid displacements, velocities, and temperatures transfer between the fluid and solid regions across the fluid-solid interface, with the fluid mesh updating between sequential time steps. The algorithm continues to loop through the solid and fluid analyses until convergence is reached for that time step. Convergence in the stagger loop is based on the quantities being transferred at the fluid-solid interface.

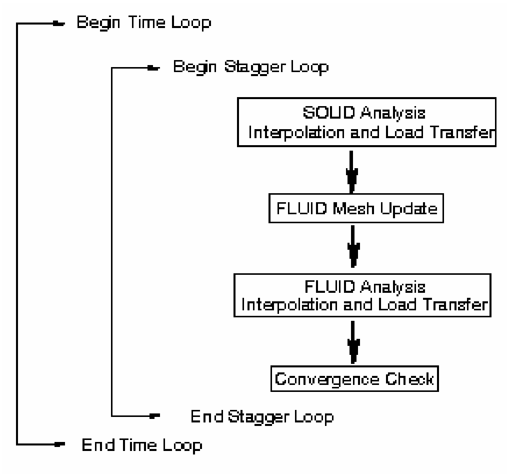


Fig. 1. Fluid-solid sequential coupling algorithm for the time and stagger loops.

In the case of moving boundaries the equations of motion can be based on an Eulerian (fixed) frame of reference. The governing equations may also be formulated in a Lagrangian frame of reference, i.e. the reference frame moves with the fluid particles. Both formulations have their advantages and disadvantages. With the Eulerian framework it is not straightforward to solve problems involving moving boundaries or deforming domains. While such problems are more suitable for a Lagrangian framework, in practice the mesh distortions can be quite severe leading to mesh entanglement and other inaccuracies. A pragmatic way around this problem is to move the mesh independent of the fluid particles in such a way as to minimize the distortions. This is the Arbitrary Lagrangian Eulerian (ALE) formulation, which involves moving the mesh nodal points in some heuristic fashion so as to track the boundary motion/domain deformation and at the same time minimizing the mesh degradation.

The ALE formulation for describing fluid flow in the fluid domain for FSI problems can be written for the equation of momentum as:

$$r_F\left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v}\right) - \nabla \cdot s_F = \vec{f}_F \qquad (1)$$

and for the equation of continuity:

$$\nabla \cdot \vec{v} = 0\,, \qquad (2)$$

where $\vec{v}$ is the fluid velocity vector; r_F is the fluid mass density; s_F is the total fluid stress tensor and $\vec{f}_F$ is the applied body force vector in the fluid domain.

Transient dynamic analysis (sometimes called time-history analysis) is a technique used in ANSYS to determine the time-varying displacements, strains, stresses, and forces in the structure as the dynamic response of the membrane structure under the action of the time-dependent fluid forces from the fluid region. The basic equation of motion solved by a transient dynamic analysis can be expressed according to the equation of momentum in the structural domain:

$$r_S \frac{\partial^2 \vec{u}}{\partial t^2} - \nabla \cdot s_S = \vec{f}_S\,, \qquad (3)$$

where r_S is the density of the structural material, $\vec{u}$ is the displacement, s_S is the stress tensor for the elastic structural material and $\vec{f}_S$ is the applied body force in the structural domain.

The coupling conditions for the interface between the fluid and the solid region are kinematical and equilibrium conditions. The kinematical condition is the no-slip condition, i.e., continuity in velocity expressed as:

$$\vec{v}_i = \dot{\vec{u}}_i\,, \qquad (4)$$

and the equilibrium condition is interface continuity in tractions replaced by continuity of stresses written as:

$$s_{ij}^{S} n_j^S + s_{ij}^{F} n_j^F = 0 \,, \tag{5}$$

where n_j^S is the outward unit normal to the solid at the interface between solid and fluid in the deformed configuration, so as $n_j^S = -n_j^F$ (indexes i and j define directions of components according to axes of the applied coordinate system, $i, j = X, Y, Z$).

These equations are expressed in terms of partial differential equations that are discretized with a finite element based technique to be used in the numerical solving procedures.

2. HIGH RESOLUTION MICROSTRUCTURED CANTILEVER SENSOR FOR FLUID FLOW VELOCITIES MEASURING

In fluid mechanics there is a large necessity for high-resolution velocity measurement techniques. Beside well-known methods like laser doppler anemometry where the flow velocity is contactless detected by laser beam, or hot-wire anemometry with very high spatial and temporal resolution there remains a demand for the development of new techniques. This is especially important for turbulent flows because hot-wire anemometers that have been used for several decades as suitable velocity of flow detectors with high resolution velocity are not quite suitable for turbulent flows when small scale effects are investigated. Hot-wire sensors are heated by a current while being cooled simultaneously by the passing fluid. Operated in a constant temperature mode the required current yields the information of the fluid velocity. And this functions very well in macro scale with laminar flows when the sensors can be of large volumes. But for turbulent flow with effects of the turbulent velocity fluctuations it is necessary to have many small devices to represent the velocity field. However, small dimensions of such sensors cause a very small heat. Accordingly, despite of the success of hot-wire anemometry this technique has reached its limits. Their wires with diameters smaller than $1mm$ aren't mechanically stable enough to be used in flow experiments. The required aspect ratio (length to diameter) of 100:1 fixes their length to a lower limit of $100mm$. Another limitation is imposed on the hot-wire anemometry in water experiments. Here the overheat ratio of the wires, the temperature difference to the flowing fluid, have to be much smaller than in air, which drastically confines their sensitivity. In addition, the wires need to be electrically isolated which increases the thermal mass of the sensor and makes the system less sensitive. These limiting factors of the hot-wire anemometry were the starting point for the development of a new type of anemometer with high resolution of flow velocity sensing especially in micro scale flows with turbulent velocity fluctuations.

The idea for the working principle of the new sensor was based on the atomic force microscope (AFM) where the AFM utilizes a sharp probe moving over the surface of a sample for raster scanning. In the original case of the AFM, the probe is a tip on the end of a cantilever that bends in response to the force between the tip and the sample. For the lever bending detection most AFMs employ an optical lever technique. On the basis of this technique the idea of silicon micro-structured cantilevers as the sensing element for transforming fluid flow velocities into extreme small deflections of the cantilevers was arisen. Herewith, to perform local velocity measurements in a fluid, the detection of the defection of the cantilever due to the fluid effect is observed. In contrast to the usual application in AFM, in this type fluid loads act along the whole surface of the cantilever instead of just on the tip. Fig. 2 illustrates how this sensor works. When the fluid flows the cantilever flexes and the light from a laser focused on the tip of the cantilever reflects onto a photo-diode that serves as the position detector where the changing of the position of the reflex beam is detected. By measuring the signal from the photo-diode the bending of the cantilever can be recorded. Since the cantilever obeys Hooke's Law for small displacements, the deflection of the tip of the cantilever can be described by:

$$s = \frac{l^3}{8}\frac{F}{E \cdot I_a}, \tag{1}$$

where: E is Young's modulus of elasticity, F is the force that fluid acts on the cantilever and $I_a = \frac{1}{12}hw^3$ represents the geometrical moment of inertia of a console with length l, width w and height h. Fluid force that depends on the normal component of the fluid flow velocity v, density of the fluid r and the drag coefficient c_s can be expressed by:

$$F = \frac{1}{2} \cdot c_d \cdot r \cdot v^2 \cdot j \cdot w \tag{2}$$

If the deflection of the cantilever is able to be measured then, according to Eq. 1 and Eq. 2 the normal component of the fluid velocity averaged over the cantilever and independent of the width of the cantilever can be finally calculated by:

$$v = \sqrt{\frac{4}{3}\frac{s \cdot E \cdot h^3}{c_d \cdot r \cdot l^4}}\,. \tag{3}$$

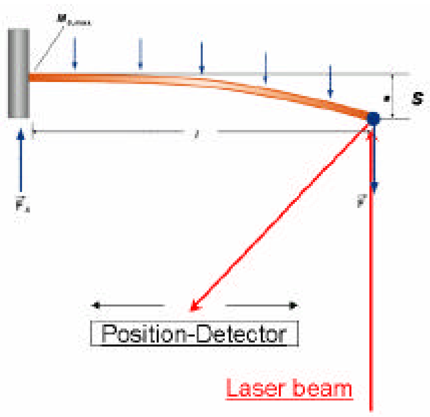


Fig. 2. Working principle of measuring cantilever deflection by using a laser and a position detector

On the basis of this principle, micromechanical sensing devices for detecting fluid flow velocities with high sensitivity, whose the initial schematic representation of the silicon micro-structured cantilever is shown in Fig. 3., were designed and produced by applying micromechanical technology processes shown in Fig. 4. in Center for Micro- and Nanotechnologies, TU Ilmenau, Germany.

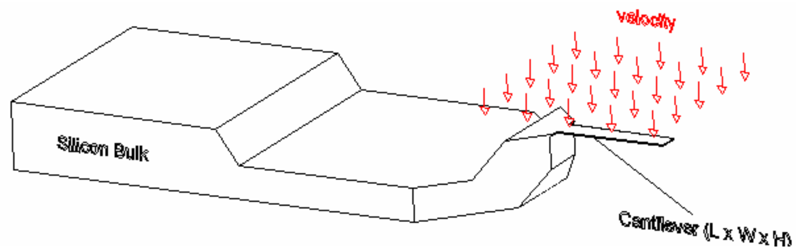


Fig. 3. Initial schematic representation of a silicon micro-structured cantilever for fluid flow velocity detecting

In this way a set of high resolution microstructured cantilever sensors with basic dimensions of the cantilevers $80 < L < 300mm$, $15 < W < 100mm$ and $1.4 < H < 1.6mm$ $1.4 < \mathrm{H} < 1.6\mu\mathrm{m}$ for measuring typical fluid flow velocities ca. $10\frac{m}{s}$ and with resonance frequencies $> 100kHz$ was realized.

In Fig. 5. the realized micro-structured cantilever with the length of $150mm$, width of $50mm$ and thickness of $1.5mm$ used as the sensing element is shown. To perform local velocity measurements in a fluid with this sensing device, the detection of the defection of the cantilever due to the fluid effect should be observed.

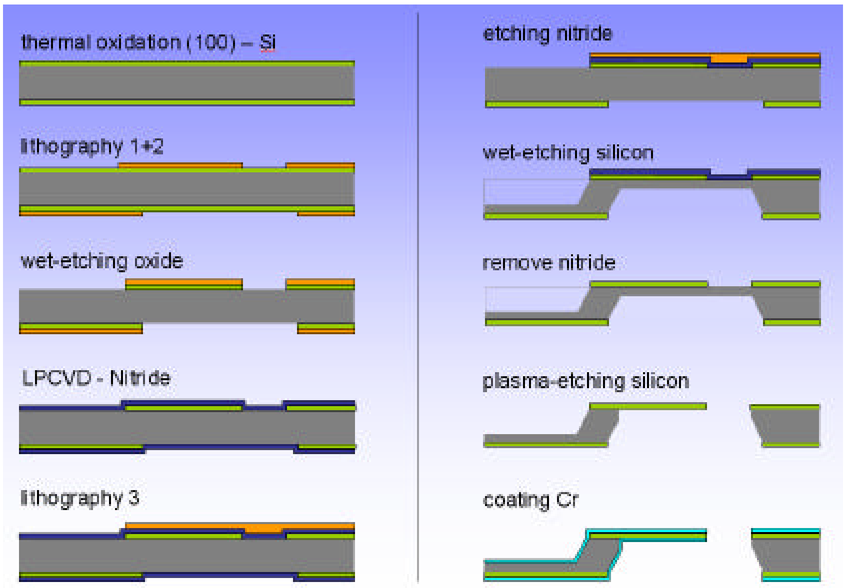


Fig. 4. Micromechanical technology processes of cantilever production

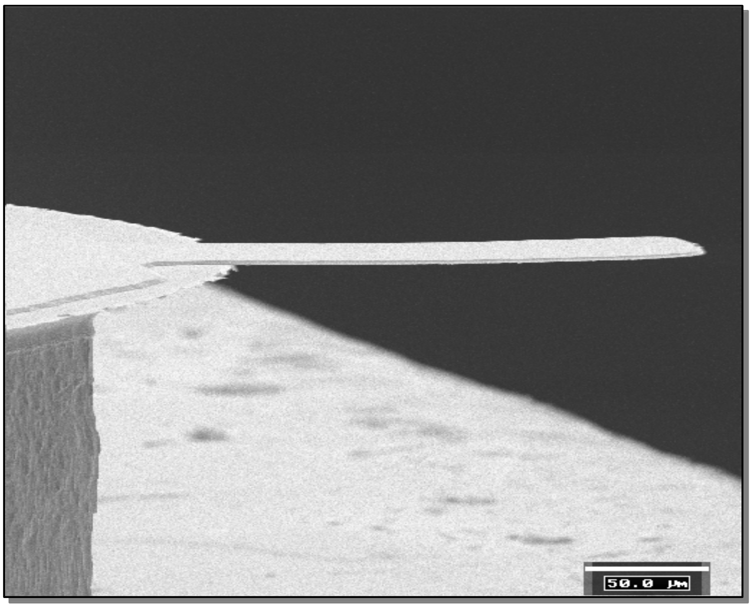
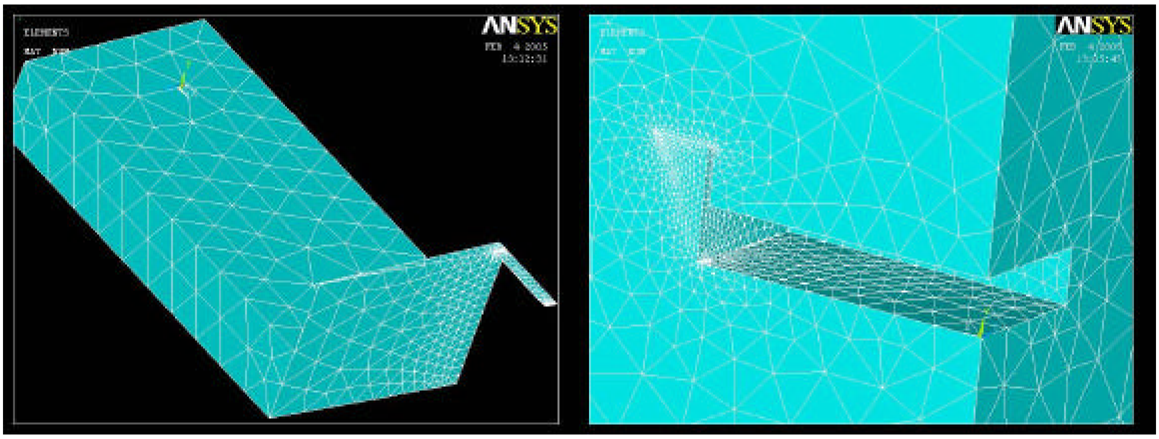


Fig. 5. Micro-structured cantilever for fluid flow velocity detecting

3. MODELING MICROSTRUCTURED CANTILEVER SENSOR

In order of getting to know with dynamical behaviour of the proposed high resolution microstructured cantilever sensor for liquids flow measuring and for the further processes of its optimization the coupled fluid-structure integration was performed. For that purposes a sequential weak coupling algorithm of a 3D coupled-field analysis of the simulation software ANSYS was utilized.

For the beginning the solid model of the microsized cantilever structure was firstly made and then the finite element mesh, shown in Fig. 4. (a), followed together with the defining appropriate boundary conditions for the solid, material properties and necessary solution options for a structural analysis. SOLID45 — 3D Structural Solid element was used for tree dimensional modeling of solid structures. Eight nodes having three degrees of freedom (translations in the nodal X, Y and Z directions) at each node define this element.



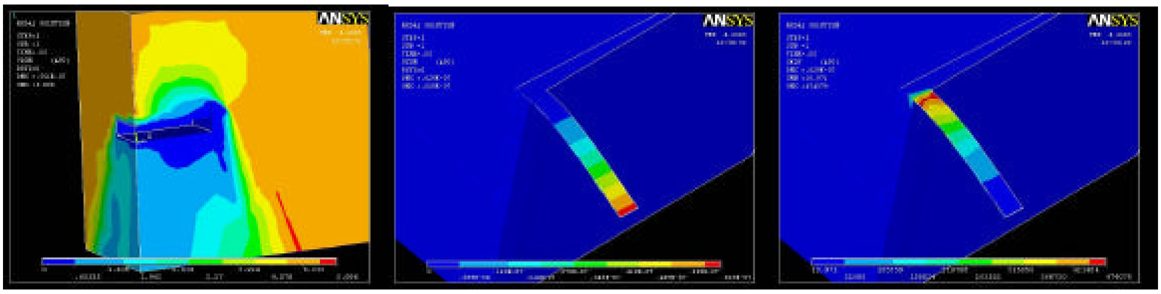
(a) (b) (zoom)

Fig. 4. 3D meshed models of the microsized cantilever structure (a) and fluid region (b) (symmetrical part)

Next, the fluid model and the finite element mesh for the fluid region were created (Fig. 4. (b)). The appropriate boundary conditions for the fluid region and material properties were applied together with required solution options for fluid analysis. FLUID142 — 3D Fluid element with eight nodes is used for modeling transient state of a single-phase fluid system in tri-dimensional analyses. For this element, the velocities are obtained from the conservation of momentum principle, and the pressure is obtained from the conservation of mass principle. A segregated sequential solver algorithm is used; that is, the matrix system derived from the finite element discretization of the governing equation for each degree of freedom is solved separately. The flow problem is nonlinear and the governing equations are coupled together. The sequential solution of all the governing equations, combined with the update of any temperature- or pressure-dependent properties, constitutes a global iteration. The number of global iterations required to achieve a converged solution may vary considerably, depending on the size and stability of the problem. For using element FLUID142 in a fluid-solid interaction analysis, as in this case, KEYOPT(4)=1 allows displacement DOFs (UX, UY and UZ) to specify motion of boundaries in ALE formulation.

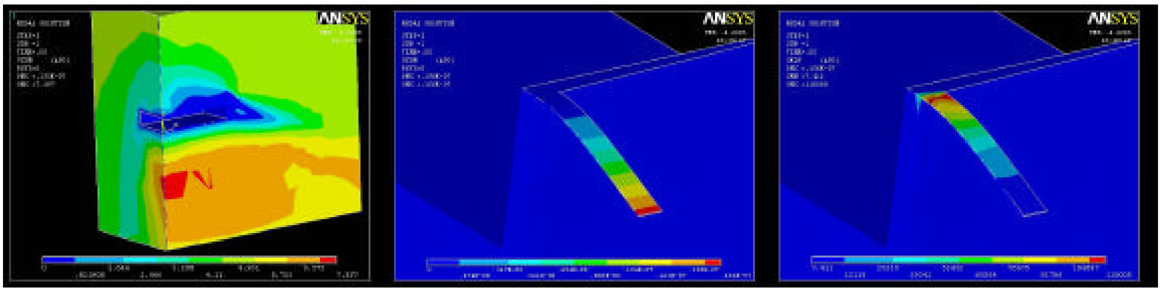
The next step was to flag fluid-solid interfaces where load transfer taken place. This was necessary because load transfer between solid and fluid regions occurs only across these surfaces. The final part was setting options needed for fluid-solid interaction solution and the analysis was ready for performing.

For this paper some results of coupled-field analyses on the proposed high resolution microstructured cantilever sensor for liquids flow measuring are chosen. The fluid velocity disturbances (VSUM), cantilever deflections (USUM) and Von Mises stress distributions (SEQV) are presented on the following figures respectively depicted by (a), (b) and (c) for the fluid flow of air with the velocity of $5\frac{m}{s}$ applied in different directions: in the Y direction (Fig. 5.), in the XY plane under an angle of attack of $45°$ (Fig. 6.) and $135°$ (Fig. 7.) from the horizontal and in the YZ plane under an angle of attack of $45°$ (Fig. 8.) from the horizontal.



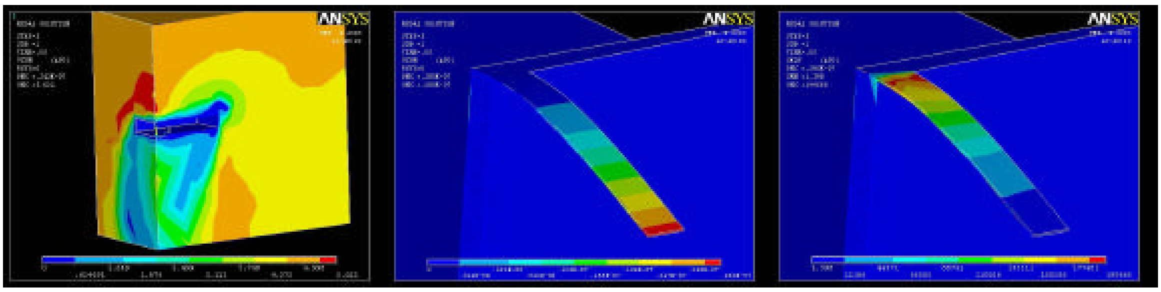
(a) (b) (zoom) (c) (zoom)

Fig. 5. Symmetrical results of the coupled fluid-structured analysis for the fluid flow in the Y direction (symmetrical parts)



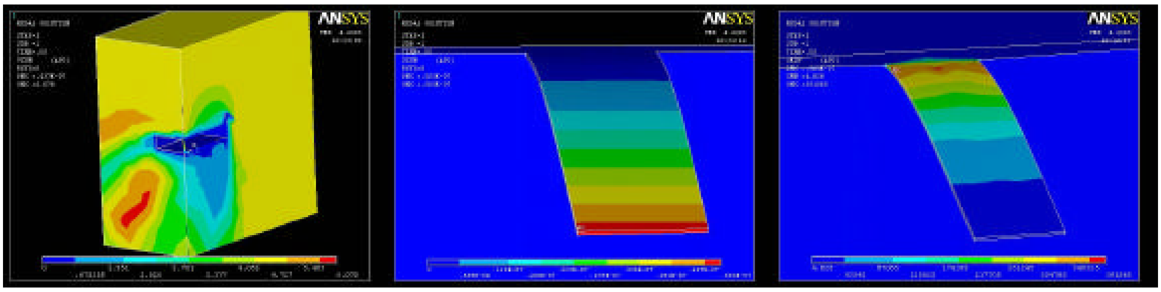
(a) (b) (zoom) (c) (zoom)

Fig. 6. Symmetrical results of the coupled fluid-structured analysis for the fluid flow in the XY plane in the direction of $45°$ from the horizontal (symmetrical parts)



(a) (b) (zoom) (c) (zoom)

Fig. 7. Symmetrical results of the coupled fluid-structured analysis for the fluid flow in the XY plane in the direction of $135°$ from the horizontal (symmetrical parts)



(a) (non-symmetrical part) (b) (whole cantilever, zoom) (c) (whole cantilever, zoom)

Fig. 8. Non-symmetrical results of the coupled fluid-structured analysis for the fluid flow in the YZ plane in the direction of $45°$ from the horizontal

4. CONCLUSION

Theoretical systematization and the modeling procedure for the complex simulation of fluid-solid interaction problems that happen when fluids flow around structures by a sequential weak coupling algorithm of a 3D coupled-field analysis in the simulation package ANSYS were presented for a high resolution microstructured cantilever sensor for measuring flows of liquids especially in turbulence regimes that works on the principle of transforming fluid flow velocity into extreme small deflections of the cantilever. The reported results of the simulations for the fluid velocity disturbances, cantilever deflections and Von Misses stress distributions can be further used for making improvements, optimization processes and wider dimensions decreasing of the proposed sensor design for making better geometrical and form variants especially regards of minimizing fluid flow resistance.

The next simulation steps will be directed in making more complex coupled-field integrations of this cantilever type sensor with strain gauges and piezoresistive ceramics for detecting small cantilever deformations and obtaining valid dynamical behaviour of new multicomponent velocity sensor models integrated with pressure and thermal parts as complex multidisciplinary micromechanical systems that could be reliably used for designing new types of high resolution microstructured cantilever sensors for liquids flow measuring.

5. ACKNOWLEDGEMENTS

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[9] ANSYS Documentation

Authors:

Ass. Miloš Miloševic, M.Sc.
Prof. Života Živkovic, Ph.D.
Faculty of Mechanical Engineering
A. Medvedeva 14, 18000 Niš, Serbia & Montenegro
mmilos@masfak.ni.ac.yu

Dipl.-Ing. Jörg Burgold
Prof.Dr.-Ing.Habil. Helmut Wurmus
Technische Universität Ilmenau
PF 100565, D-98684 Ilmenau
helmut.wurmus@tu-ilmenau.de