# PROCEEDINGS

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# PREFACE

These proceedings contains the papers presented at the Forth ($29^{th}$ Yu) International Congress of Serbian Society of Mechanics held in Vrnjačka Banja during the period $4^{th}$ – $7^{th}$ June, 2013.

Theoretical and Applied Mechanics is a subject of great importance in the developing of science and technology. The aim of the Congress is to provide a forum to exhibit the progress in this field during the past years and a place to further the interaction between of modern theoretical and applied mechanics, as well as modern engineering sciences.

The papers, contributed by authors from all around the globe, have been separated into 7 sections which cover the main areas of interest: \`Plenary Lectures\`, Section A, Section B, Section C, Section D and two Mini-symposia.

We would like to express our gratitude to all members of the Scientific Committee and also to the participants for their engagement in organizing of the Congress, including the preparation of manuscripts to be published in the Journal Theoretical and Applied Mechanics, Scientific Technical Review and Journal of Serbian Society for Computational Mechanics.

It gives us great pleasure to express our deep appreciation for the great long-standing support that Prof. Dr. Nikola Hajdin, President of the Serbian Academy of Sciences and Arts, has given to the promotion of all aspects of theoretical and applied mechanics in Serbia.

Last, the Congress organizing committee wishes to acknowledge the collaboration of the Ministry of Education, Science and Technological Development of the Republic of Serbia, Serbian Academy of Sciences and Arts, Municipality Vrnjačka Banja and many supporting members of the Serbian Society of Mechanics.

S. MAKSIMOVIĆ & T. IGIĆ
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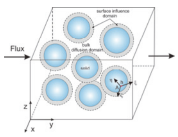


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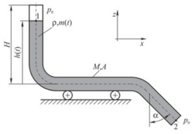

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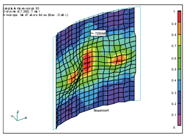

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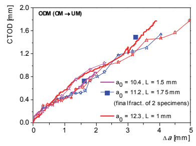

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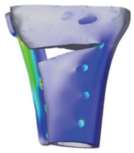

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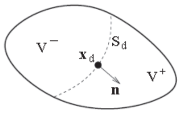


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# ROLE OF OSCILLATORY SHEAR INDEX IN PREDICTING THE OCCURRENCE AND DEVELOPMENT OF PLAQUE

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**Abstract.** The paper presents theoretical basis and results obtained by calculation of blood flow in carotid artery bifurcation, whereby the emphasis is placed on the plaque occurrence analysis based on oscillatory shear index (OSI). OSI is the temporal fluctuation of low and high average shear stress. The endothelial shear stress is a major factor that affects the formation of plaque phenomenon. There is a complex hemodynamic conditions in these areas where local fluid flow dictates the occurrence and development of plaque. Favorable conditions for the plaque development occurring in areas characterized by low shear stress, while areas with higher values of OSI index are not susceptible. Arterial bifurcations are the places in vascular tree where atherosclerosis mainly occurs. OSI index response to the appearance of plaques in the common carotid artery and branches (CCA, ECA and ICA) are considered on three out of eight possible combinations of plaque locations. Algorithm for the calculation of OSI index are embedded in software PAK-F and the results are written in FEMAP neutral and Paraview VTK file format.

## 1. Introduction

The relationship between flow in the arteries, the wall shear stress distribution and the sites where diseases can develop has motivated much of a research on arterial flow in the last decade. Wall shear stress (WSS) is the main flow-related factor affecting the distribution of atherosclerosis. It is now accepted that the sites where shear stresses are extreme or change rapidly in time or space are critical in developing diseases [1,2]. Atherosclerosis occurs predominantly at branching locations of the vascular tree, where the arteries have relatively complex geometry that results in a disturbed behavior of a blood flow [3]. There is a need to identify, in vivo, early plaques that are likely to develop characteristics of either vulnerable plaque or lumen obstruction. Then selective interventions could be applied to these areas in order to avoid subsequent cardiac events [4]. Non-invasive diagnostic procedures such as MRI are often used in this context, but do not provide information on time-dependent pressures and wall shear stresses - key quantities considered to be partially responsible for the formation and development of related pathologies.
Numerical methods, such as finite element analysis (FEA), allow sufficiently accurate determination of transient fields of pressures and wall shear stresses. Finite element models

allow one to simulate experimental changes caused by variations of some parameters, and analyze the effects and influences of a single component within the phenomenon investigated [5,6].

## 2. Oscillatory shear index (OSI)

Temporal oscillations of low and high average shear stress are measured across oscillatory shear index (OSI). Shear vector can be calculated from the stress tensor $\boldsymbol{\sigma}$ and the normal vector to the surface $\mathbf{n}$ :

$$\mathbf{t} = \boldsymbol{\sigma} \cdot \mathbf{n} \quad . \tag{1}$$

Surface shear vector $\mathbf{t}_s$ is defined as the tangential component of the shear stress:

$$\mathbf{t}_s = \mathbf{t} - (\mathbf{t} \cdot \mathbf{n})\mathbf{n} \, . \tag{2}$$

The scalar value of the mean shear stress $\tau_{mean}$ is defined as the average intensity values of the shear vector:

$$\tau_{mean} = \left| \frac{1}{T} \int_0^T \mathbf{t}_s dt \right| . \tag{3}$$

while the scalar $\tau_{mag}$ is defined as the average value of the intensity of the shear vector:

$$\tau_{mag} = \frac{1}{T} \int_0^T |\mathbf{t}_s| dt \, . \tag{4}$$

Oscillatory shear index (OSI) is defined by the expression:

$$OSI = \frac{1}{2} \left( 1 - \frac{\tau_{mean}}{\tau_{mag}} \right) . \tag{5}$$

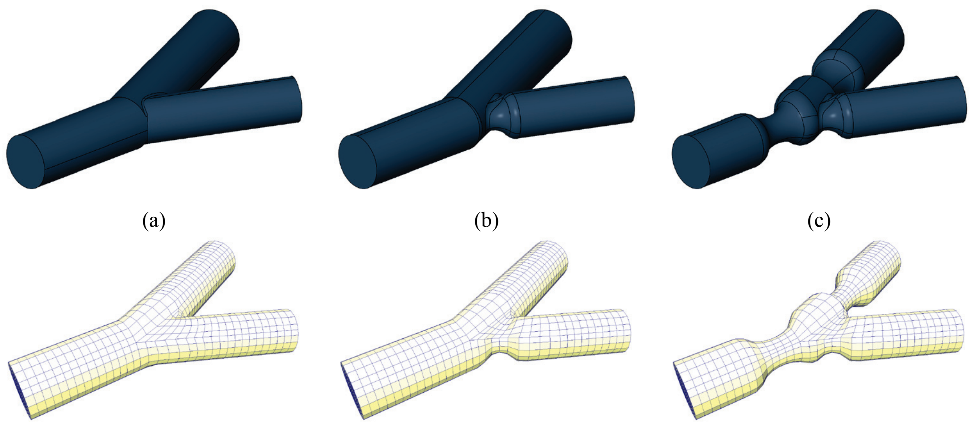
In case when $\tau_{mean} = \tau_{mag}$, their ratio is $\frac{\tau_{mean}}{\tau_{mag}} = 1$, and $OSI = 0$. On the other hand, when $\tau_{mean} = 0$, ratio is $\frac{\tau_{mean}}{\tau_{mag}} = 0$, and $OSI = \frac{1}{2}$. The value of OSI varies in the interval $[0, 0.5]$.

## 3. Generation of Finite Element Models

This problem is observed on 2D examples in the literature [7]. In this paper we observe the following cases of coronary artery bifurcation: (a) with no stenosis, (b) stenosis of the side branch, and (c) stenosis in all branches (Fig. 1). In addition, we observed coronary bifurcation model generated based on MSCT scan of patient.

CAD model of coronary bifurcation is generated in CATIA software (Fig. 1). Finite element models were generated using in-house software STL2FEM [8], thus the preparation of model also been made in software GOM Inspect (polygonization, setting borders of model). Software STL2FEM, based on multiblock approach, is very suitable when dealing with irregular geometries, especially hexahedral elements meshing of the irregular anatomical structures (Fig. 1).

Finite element simulations of coronary flow are performed using software PAK-F [9]. Blood is approximated as an incompressible Newtonian fluid with a density of 1050 kg/m$^3$ and a dynamic viscosity of 0.003675 Pas [9]. One cardiac cycle (0.89 s) is simulated in 20 steps with time step size of 44.49 ms. Maximal diastolic flow velocity in the inlet is 33 cm/s. Velocity profile used for simulating is pulsatile flow. Velocities of nodes on the arterial wall are equal to zero. We calculate ESS, OSI index, velocity, and pressure throughout cardiac cycle.



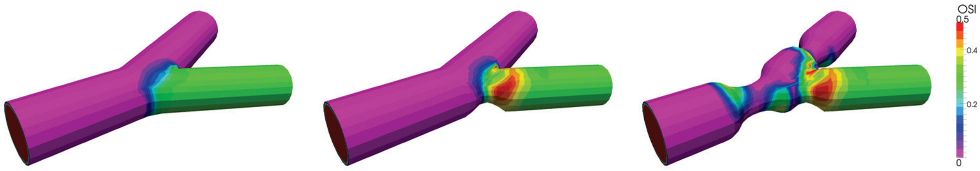
(a) (b) (c)

(d) (e) (f)

**Figure 1.** CAD and FE models of coronary artery bifurcation: (a, d) model with no stenosis, (b, e) model with stenosis on side branch, (c, f) model with stenosis on all branches.

## 4. Results and Discussion

Analyses by 3D models that consider only the ideal geometry of arterial bifurcations are not suitable to draw conclusions that will come to develop the disease (Fig. 2). In cases where the pathology is modeled, one can predict how it will thrive. This adds to the importance of efforts to generate high-quality patient-specific models, and software STL2FEM contributes to these efforts. On example of real coronary bifurcation it is clearly visible areas where change in the direction of shear stress is negligible, so that the oscillatory shear index, with the field endothelial shear stress, modeling the distribution of LDL and other tools and techniques can be used to predict the occurrence and development of pathology (Fig. 3).




(a) (b) (c)

**Figure 2.** Oscillatory Shear Index (OSI) for observed geometrically ideal cases.


**Figure 3.** Oscillatory Shear Index (OSI) for observed patient-specific case.

## 5. Conclusion

A very short time required to generate the model allows the treatment of large number of patients. This model offers the possibility for monitoring patients over time, which can become a part of their medical records. Thanks to rapid modeling, this methodology not only allows detailed characterization of arterial plaque at a given moment in time but, applied routinely, can give an insight how the plaques change over time and what antecedent features predict their future behavior.

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