

# NUMERIČNO MODELIRANJE SKLOPLJENIH SISTEMOV

## UČNI NAČRT PREDMETA/COURSE SYLLABUS

<b>Predmet:</b>	NUMERIČNO MODELIRANJE SKLOPLJENIH SISTEMOV
<b>Course title:</b>	NUMERICAL MODELLING OF COUPLED SYSTEMS
<b>Članica nosilka/UL Member:</b>	UL FS

<b>Študijski programi in stopnja</b>	<b>Študijska smer</b>	<b>Letnik</b>	<b>Semestri</b>	<b>Izbirnost</b>
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Strojništvo, tretja stopnja, doktorski	Ni členitve (študijski program)	1. letnik, 2. letnik	Celoletni	izbirni
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**Univerzitetna koda predmeta/University course code:**

0033420

**Koda učne enote na članici/UL Member course code:**

7012

<b>Predavanja /Lectures</b>	<b>Seminar /Seminar</b>	<b>Vaje /Tutorials</b>	<b>Klinične vaje /Clinical tutorials</b>	<b>Druge oblike študija /Other forms of study</b>	<b>Samostojno delo /Individual student work</b>	<b>ECTS</b>
90					160	10

**Nosilec predmeta/Lecturer:**

Božidar Šarler, Miroslav Halilović,  
Nikolaj Mole

**Izvajalci predavanj:**

Miroslav Halilović, Nikolaj Mole, Božidar Šarler

**Izvajalci seminarjev:**

**Izvajalci vaj:**

**Izvajalci kliničnih vaj:**

**Izvajalci drugih oblik:**

**Izvajalci praktičnega usposabljanja:**

**Vrsta predmeta/Course type:**

Izbirni predmet /Elective course

**Jeziki/Languages:**

Predavanja/Lectures:

Angleščina, Slovenščina

Vaje/Tutorial:

Angleščina, Slovenščina

**Pogoji za vključitev v delo oz. za opravljanje študijskih obveznosti:****Prerequisites:**

Veljajo splošni pogoji za doktorski študij.

General prerequisites for the third level studies.

**Vsebina:****Content (Syllabus outline):**

- Uvod v multifizikalne probleme: Problematika analize tehniških sestavov iz različnih gradiv ali medijev z vidika sočasnosti različnih fizikalnih pojavov. Identifikacija prostorskih podobmočij, časovnih domen ter fizikalnih pojavov, določitev medsebojnega vpliva. Klasifikacija problemov na multifizikalne in večobmočne probleme. Primeri sklopljenih problemov iz področij mehanike kontinuuma, mehanike fluidov, prevoda toplote in elektromagnetizma.
- Matematični modeli in njihove lastnosti: Vodilne enačbe posameznih fizikalnih pojavov in njihove lastnosti. Enobmočni in večobmočni problemi, multifizikalni problemi. Robni pogoji in pogoji fizikalno konsistentnega prehoda, karakterizacija soodvisnosti med veličinami fizikalno sklopljenih sistemov. Pristopi k modeliranju multifizikalnih problemov glede na stopnjo sklopljenosti, nelinearnost v odzivu ter časovno soodvisnost. Izbor modela v odnosu na cilj in kriterij, validacija modela.
- Numerično reševanje: Izbira primerne numerične metode (MKR, MKE, MRE, MKV) glede na izkazano naravo problema. Prostorska in časovna diskretizacija iz vidika medsebojne povezanosti, strategije numeričnega

- Introduction to multiphysics problems: On the analysis of technical systems composed from different materials or media considering simultaneous interaction between different physical phenomena. Identification of space subdomains, time scales and physical phenomena; determination of their mutual influence. Classification of problems to multiphysics and multidomain problems. Examples of coupled problems from the fields of continuum mechanics, fluid mechanics, heat transfer and electromagnetism.
- Mathematical models and their properties: Governing equations of several physical problems and their properties. One-domain and multidomain problems, multiphysics problems. Boundary conditions and interface conditions, characterization of interdependence between physical variables of coupled systems. Approaches to modelling of multiphysics problems regarding degree of coupling, nonlinearity of response and time simultaneity. About choosing an adequate model regarding the prescribed analysis criteria; validation of the model.
- Advanced numerical solution methods: On the choice of adequate numerical method (FEM, FDM, BEM,

<p>reševanja časovne integracije glede na stopnjo sklopljenosti in nelinearnosti. Računalniške simulacije problemov iz vidika časovne potratnosti in eventualne poenostavitve numeričnih modelov. Paralelno reševanje in sinhronizacija. Uporaba sodobnih računalniških tehnologij in programov.</p> <ul style="list-style-type: none"> <li>• Simuliranje tehnoloških procesov: Obravnava primerov mehanske interakcije med sistemi (kontakt med deformabilnimi telesi, interakcija med trdnino in fluidom) in fizikalne sklopljenosti (elektromagnetizem, prevod toplote, mehanika). Simuliranje procesov plastičnega preoblikovanja, procesov kontinuiranega litja z valjanjem, varjenja, induktivnega segrevanja, toplotnih obdelav, ...</li> </ul>	<p>FVM) regarding nature of the problem. Space and time discretization in a view of their mutual interaction; strategies used for time integration regarding the degree of physical coupling and problem nonlinearity. Computer simulations of problems in view of time consumption and possible simplifications of numerical models. Parallel computations and computational process synchronization. Modern computation technologies and programs.</p> <ul style="list-style-type: none"> <li>• Simulations of manufacturing processes: Analyses of mechanical interactions between systems (contact between deformable bodies, fluid-structure interactions) and analyses of physical coupling (electromagnetism, heat transfer, mechanical deformation) occur. Case studies: simulation of processes of metal forming, continuous casting and rolling, welding, inductive heating, heat treatment...</li> </ul>
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### Temeljna literatura in viri/Readings:

- [1] Radaj D.: Heat Effects of Welding. Temperature Field, Residual Stress, Distortion; Springer-Verlag, Heidelberg, 1992. [COBISS.SI-ID - 626459]  
[2] O.C. Zienkiewicz, R.L. Taylor: The Finite Element Method for Solid and Structural Mechanics, Sixth Edition, Elsevier, 2006. [COBISS.SI-ID - 10942486]  
[3] E.M. Alawadhi: Finite Element Simulations using ANSYS, CRC Press, 2010. [COBISS.SI-ID - 11713307]  
[4] H. J. P. Morand, R. Ohayon: Fluid Structure Interaction: Applied Numerical Methods, Wiley & Sons, 1995. [COBISS.SI-ID - 39716353]

### Cilji in kompetence:

#### Cilji:

Kot osnovni cilj gre jemati zavedanje o fizikalni sklopljenosti v večini tehniških sistemov ter stopnji sklopljenosti, ki posledično bolj ali manj vpliva na posamični fizikalni odziv. Ob ustreznem razumevanju posamičnih fizikalnih mehanizmov in njihove medsebojne interakcije je cilj študenta usposobiti za najzahtevnejše razvojno usmerjene analize na področju kompleksnih konstrukcijskih sestavov ter izdelovalnih tehnologij.

### Objectives and competences:

#### Goals:

The principal message of the course is to become aware of physical coupling in most of the technical systems and of the degree of coupling, which affects more or less the individual physical phenomenon response. By acquiring proper understanding of several physical mechanisms and their mutual interaction it is the aim to qualify student for pretentious development analyses in the field of complex physical systems and manufacturing

<p><b>Kompetence:</b></p> <p>Študent osvoji razumevanje dejavnikov, ki opredeljujejo odziv v tehniških sistemih zaznamovanih z več fizikalnimi pojavi hkrati. Na tej osnovi se bo znal odločiti, kako pristopiti k analizi delovanja heterogenih mehanskih sestavov in k analizi vrste tehnoloških postopkov. Znal bo postaviti fizikalno objektivne numerične modele, na osnovi katerih bo s sofisticiranimi računskimi orodji lahko kompetentno zasledoval učinke predpostavljenih vhodnih parametrov.</p>	<p>technologies.</p> <p><b>Competences:</b></p> <p>Student acquires the understanding of factors that determine response of technical systems with several physical phenomena interacting simultaneously. With that knowledge, student will know how to properly approach to the analysis of heterogeneous mechanical systems as well as to the analysis of different kind of technological processes. Student will also acquire knowledge on how to prepare physically objective numerical models, which can be used subsequently, with a support of well developed computer softwares provided, to asses competently the effects of prescribed input parameters by simulation.</p>
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<p><b>Predvideni študijski rezultati:</b></p> <p>Študent osvoji razumevanje dejavnikov, ki opredeljujejo odziv v tehniških sistemih zaznamovanih z več fizikalnimi pojavi hkrati. Na tej osnovi se bo znal odločiti, kako pristopiti k analizi delovanja heterogenih mehanskih sestavov in k analizi vrste tehnoloških postopkov. Znal bo postaviti fizikalno objektivne numerične modele, na osnovi katerih bo s sofisticiranimi računskimi orodji lahko kompetentno zasledoval učinke predpostavljenih vhodnih parametrov.</p>	<p><b>Intended learning outcomes:</b></p> <p>Student acquires the understanding of factors that determine response of technical systems with several physical phenomena interacting simultaneously. With that knowledge, student will know how to properly approach to the analysis of heterogeneous mechanical systems as well as to the analysis of different kind of technological processes. Student will also acquire knowledge on how to prepare physically objective numerical models, which can be used subsequently, with a support of well developed computer softwares provided, to asses competently the effects of prescribed input parameters by simulation.</p>
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<p><b>Metode poučevanja in učenja:</b></p> <p>Predavanja, laboratorijske vaje, seminarsko delo, e-izobraževanje, konzultacije. Seminarsko delo v čim večji meri navezuje se na področje doktorskega raziskovanja. Študij z uporabo priporočene literature.</p>	<p><b>Learning and teaching methods:</b></p> <p>Lectures, laboratory practice &amp; seminar work, e-education, consulting. The seminar work is related, as much as possible, to the student's doctoral research field. Study on a recommended literature basis.</p>
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<b>Načini ocenjevanja:</b>	<b>Delež/Weight</b>	<b>Assessment:</b>
Ustni izpit, poročilo o seminarskem delu. Pogoji za opravljanje ustnega izpita je uspešno izdelano in pozitivno ocenjeno seminarsko delo. • projekt (seminarsko delo) (70%) • ustno izpraševanje (30%) Oral exam, report on seminar work. The condition for admission to oral exam is successful completion of seminar work, rewarded with a passing grade. • project (seminar work) (70%) • oral examination (30%)		Oral exam, report on seminar work. The condition for admission to oral exam is successful completion of seminar work, rewarded with a passing grade. • project (seminar work) (70%) • oral examination (30%)

<b>Ocenjevalna lestvica:</b>	<b>Grading system:</b>
5 - 10, pri čemer velja, da je pozitivna ocena od 6 - 10	5 - 10, a student passes the exam if he is graded from 6 to 10

#### **Reference nosilca/Lecturer's references:**

##### **prof. dr. Božidar Šarler**

ZUPAN, Bor, PEÑA-MURILLO, Gisel Esperanza, ZAHOR, Rizwan, GREGORC, Jurij, ŠARLER, Božidar, KNOŠKA, Juraj, GAÑÁN-CALVO, Alfonso M., CHAPMAN, Henry N., BAJT, Saša. An experimental study of liquid micro-jets produced with a gas dynamic virtual nozzle under the influence of an electric field. *Frontiers in molecular biosciences*. Jan. 2023, vol. 10, str. 1-10, ilustr. ISSN 2296-889X. <https://www.frontiersin.org/articles/10.3389/fmolb.2023.1006733/full>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=143936>, DOI: 10.3389/fmolb.2023.1006733. [COBISS.SI-ID 138668547], [JCR, SNIP, WoS, Scopus]

VERTNIK, Robert, MRAMOR, Katarina, ŠARLER, Božidar. Solution of three-dimensional temperature and turbulent velocity field in continuously cast steel billets with electromagnetic stirring by a meshless method. *Engineering analysis with boundary elements*. Jul. 2019, vol. 104, str. 347-363, ilustr. ISSN 0955-7997. <https://www.sciencedirect.com/science/article/pii/S0955799718305010?via%3Dihub>, DOI: 10.1016/j.enganabound.2019.03.026. [COBISS.SI-ID 1474474], [JCR, SNIP, WoS do 29. 4. 2023: št. citatov (TC): 20, čistih citatov (CI): 10, čistih citatov na avtorja (CIAu): 3,33, Scopus do 6. 4. 2023: št. citatov (TC): 22, čistih citatov (CI): 12, čistih citatov na avtorja (CIAu): 4,00]

HATIĆ, Vanja, MAVRIČ, Boštjan, KOŠNIK, Nejc, ŠARLER, Božidar. Simulation of direct chill casting under the influence of a low-frequency electromagnetic field.

Applied mathematical modelling. [Print ed.]. 2018, vol. 54, str. 170-188, ilustr. ISSN 0307-904X.  
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<https://repozitorij.uni-lj.si/IzpisGradiva.php?id=141046>, DOI: 10.1016/j.camwa.2022.09.008. [COBISS.SI-ID 122502403], [JCR, SNIP, WoS, Scopus]

### **izr. prof. dr. Nikolaj Mole**

BOJINOVIĆ, Marko, MOLE, Nikolaj, ŠTOK, Boris. A computer simulation study of the effects of temperature change rate on austenite kinetics in laser hardening. *Surface & coatings technology*, ISSN 0257-8972. [Print ed.], Jul. 2015, vol. 273, str. 60-76, ilustr.

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KREBELJ, Kristjan, KREBELJ, Anton, HALILOVIČ, Miroslav, MOLE, Nikolaj. Modeling injection molding of high-density polyethylene with crystallization in open-source software. *Polymers*, ISSN 2073-4360, Jan. 2021, vol. 13, iss. 1, f. 1-15, ilustr. <https://www.mdpi.com/2073-4360/13/1/138>, doi: 10.3390/polym13010138. [COBISS.SI-ID 45067779], [JCR, SNIP, WoS do 26. 4. 2022: št. citatov (TC): 4, čistih citatov (CI): 4, čistih citatov na avtorja (CIAu): 1.00, Scopus do 9. 2. 2023: št. citatov (TC): 5, čistih citatov (CI): 5, čistih citatov na avtorja (CIAu): 1.25]

MOLE, Nikolaj, BOJINOVIĆ, Marko, KOC, Pino, ŠTOK, Boris. Effects of prior microstructure and heating rate on the depth of increased hardness in laser hardening : comparison of computer simulation and experimental results. *Metals*, ISSN 2075-4701, Dec. 2018, vol. 8, iss. 12, f. 1-16, ilustr.

<https://www.mdpi.com/2075-4701/8/12/1016>, doi: 10.3390/met8121016. [COBISS.SI-ID 16374043], [JCR, SNIP, WoS do 27. 6. 2022: št. citatov (TC): 1, čistih citatov (CI): 1, čistih citatov na avtorja (CIAu): 0.25, Scopus do 28. 3. 2023: št. citatov (TC): 2, čistih citatov (CI): 2, čistih citatov na avtorja (CIAu): 0.50]

MOLE, Nikolaj, BOBOVNIK, Gregor, KUTIN, Jože, ŠTOK, Boris, BAJSIČ, Ivan. An improved three-dimensional coupled fluid-structure model for Coriolis flowmeters. *Journal of fluids and structures*, ISSN 0889-9746, 2008, letn. 24, št. 4, str. 559-575. <http://dx.doi.org/10.1016/j.jfluidstructs.2007.10.004>. [COBISS.SI-ID 10511643], [JCR, SNIP, WoS do 8. 8. 2022: št. citatov (TC): 22, čistih citatov (CI): 17, čistih citatov na avtorja (CIAu): 3.40, Scopus do 21. 1. 2023: št. citatov (TC): 34, čistih

citativ (CI): 28, čistih citativ na avtorja (CIAu): 5.60]

**izr. prof. dr. Miroslav Halilović**

STARMAN, Bojan, HALILOVIČ, Miroslav, VRH, Marko, ŠTOK, Boris. Consistent tangent operator for cutting-plane algorithm of elasto-plasticity. Computer methods in applied mechanics and engineering. [Print ed.]. Apr. 2014, vol. 272, str. 214-232, ilustr. ISSN 0045-7825. DOI: 10.1016/j.cma.2013.12.012. [COBISS.SI-ID 13311515], [JCR, SNIP, WoS do 5. 2. 2024: št. citativ (TC): 20, čistih citativ (CI): 19, čistih citativ na avtorja (CIAu): 4.75, Scopus do 11. 1. 2024: št. citativ (TC): 23, čistih citativ (CI): 22, čistih citativ na avtorja (CIAu): 5.50]

KOVŠCA, Dejan, STARMAN, Bojan, KLOBČAR, Damjan, HALILOVIČ, Miroslav, MOLE, Nikolaj. Towards an automated framework for the finite element computational modelling of directed energy deposition. Finite elements in analysis and design. [Print ed.]. Sept. 2023, vol. 221, str. 1-12, ilustr. ISSN 0168-874X. <https://www.sciencedirect.com/science/article/pii/S0168874X23000422>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=145657>, DOI: 10.1016/j.finel.2023.103949. [COBISS.SI-ID 150969347], [JCR, SNIP, WoS do 23. 4. 2024: št. citativ (TC): 2, čistih citativ (CI): 2, čistih citativ na avtorja (CIAu): 0.40, Scopus do 21. 1. 2024: št. citativ (TC): 1, čistih citativ (CI): 1, čistih citativ na avtorja (CIAu): 0.20]

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