Characteristics of main research directions investigated at the institute and the achievements 2010−2014

Institute	Institute of Thermomechanics of the CAS, v. v. i.

The principal areas of the Institute's research in 2010-2014 were fluid dynamics, thermodynamics, dynamics of mechanical systems, mechanics of deformable solids, material diagnostics, interdisciplinary problems (e.g. fluid-structure interaction, environmental aerodynamics, biomechanics, and mechatronics), and power electromechanical systems (with emphasis on electric machines, instruments and other equipment).

Main results of the Institute of Thermomechanics in 2010-2014

2010

Thermodynamic properties of ionic liquids

Ionic liquids are a novel class of materials with unique properties and a wide range of applications such as in fuel-cell systems, nanotechnology, lubricants, heat transfer fluids or as absorbents in absorption refrigeration. Despite their potential the available data on their thermophysical properties are still fragmentary or completely missing. The knowledge of the thermophysical properties of ionic liquids facilitates their use in new applications. The liquid density and surface tension and their temperature dependence rank among the properties important in most applications. The Laboratory of Thermophysical Properties of Fluids of the Institute measured the temperature dependence of density and air-liquid surface tension of nine 1-alkyl-3-methylimidazolium-based ionic liquids with different anions at temperatures from 288 to 353 K and pressure 0.1 MPa. It was found that the surface tension and surface entropy of the ionic liquids depend on the length of the cation alkyl side chain and the size of the anion.

- Klomfar, J. – Součková, M. – Pátek J.: Temperature dependence measurements of the density at 0.1 MPa for 1-alkyl-3-methylimidazolium-based ionic liquids with the trifluoromethanesulfonate and tetrafluoroborate anion. Journal of Chemical and Engineering Data. 55(9) (2010) 4054 – 4057.
- Klomfar, J. – Součková, M. – Pátek J.: Surface tension measurements with validated accuracy for four 1-Alkyl-3-methylimidazolium based ionic liquids. Journal of Chemical Thermodynamics. 42(9) (2010) 323 – 329.

Mechanical properties of surface layers

Thin coatings have become an increasingly popular topic in material science, electronics and biomedical applications. A new ultrasonic method was developed to overcome the limitations and shortcomings of the standard methods of identification of the mechanical properties of thin coatings. The method is based on the changes of the resonant frequencies of specimens, which are caused by the presence of the deposition layers on substrates. The scope of the modified

Resonant Ultrasound Spectroscopy (RUS) method was tested on diamond layers (DLC and NCD) of 100 nm – 1µm thickness and on the plasma-sprayed coatings of alumina (100-200µm). The proposed method is particularly suitable for the investigation of in-plane elastic properties of layers and it can also be used to monitor the deposition process in situ. Furthermore, the analysis of the changes of the resonant frequency enables us to estimate the level of the residual stresses in materials and to observe the propagation of surface acoustic waves (SAW) through anisotropic media. The method was successfully tested on specimens composed of carbon layers deposited on silicon substrates. The principal investigator conducted a set of experiments at ATF KU Leuven during his stay in Belgium. The unique SAW methodology in combination with the original RUS method showed significant advantage over the standard arrangement.

- Růžek, M. - Seiner, H. - Sedlák, P. – Kruisová, A. - Landa, M.: Linearized forward and inverse problem of the resonant ultrasound spectroscopy for the evaluation of thin surface layers. Journal of the Acoustical Society of America, 2010, 128{6) 3426-3437.
- Kocourek, T. - Růžek, M. - Landa, M. - Jelínek, M. - Mikšovský, J. – Kopeček, J.: Evaluation of elastic properties of DLC layers using resonant ultrasound spectroscopy and AFM nanoindentation. Surface and Coating Technology, 2011, 205(2) 67-S70.

Mathematical and physical modelling of fluid-structure interaction in human vocal folds

New numerical models of flow in glottis were developed, in which the human vocal tract is modelled as a channel flow. The flow is described by the Navier-Stokes equations using the finite-element and finite-volume methods. The models take into account the interaction of airflow with vibrating vocal folds and describe the influence of the ventricular folds. The physiologically correspondence with the reality is ensured by setting the geometrical and physical parameters. Despite the channel symmetry, the flow is significantly asymmetrical with the size of the dominant vortices of the order of the channel cross-section. The vortices are formed in the wake behind the vibrating vocal folds, slowly flowing downstream of the vocal tract model. The Coanda effect was identified in the flow field; the air jet bends on the vibrating vocal folds randomly in one or the other direction.

The flow–induced vibrations of the vocal folds excited by the airflow from the lungs were also modelled numerically. The results predicted minimal subglottal pressures and airflow rates necessary for the phonation onset. The resulting flow parameters for the onset and the fundamental frequency of phonation were in good agreement with the physiological data known for humans. The proposed method enables us to model the influence of the shape and size of the vocal folds on the phonation onset.

The results of the numerical simulations were experimentally verified by the Particle Image Velocimetry (PIV) method on the physical models of the vocal folds with the vocal tract. The analysis of the measured data focused on the determination of the flow separation point on the vibrating surface of the vocal folds and on the evaluation of the flow velocities in the glottis region. The numerical description of the coherent structures was in good qualitative agreement with the PIV measurements. The structure of the flow field in this region is of fundamental importance for the generation of acoustic signals as the voice source.

- Punčochářová P. - Furst J. - Horáček J. - Kozel K.: Numerical solutions of unsteady flows with low inlet Mach numbers. Mathematics and Computers in Simulation, 2010, 80(8) 1795-1805.

- Sváček P. - Horáček J.: Numerical Approximation of Flow Induced Vibration of Vocal Folds. In Clavero, C.; Gracia, J.L.; Lisbona, F.J. (ed.). *BAIL 2010 - Boundary and Interior Layers, Computational and Asymptotic Methods*. Berlin: Springer, 2011, pp. 227-234.
- Šidlof P. - Doaré O. - Cadot O. - Chaigne A.: Measurement of flow separation in a human vocal folds model. Experiments in Fluids, 2011, 51(1) 123-136.

2011

Fluidic pumps for extremely dangerous liquids

The fluidic pumps are based on the principle of fluidic rectification of alternating flow without moving parts. Different flow fields in the mutually opposed flow directions are described by non-linear equations of the fluid flow. The rectification effect takes place in closed cavities with fixed solid walls, which eliminates the problem of leaks in the orifice for the mechanical driving shaft in classical pumps. The pump thus may be, e.g., a welded block of resistant material, such as Monel metal or ceramics. These pumps require no maintenance (such as tightening the sealing glands, oiling the bearings etc.). As a result, they exhibit extreme reliability and their practically unlimited life makes them suitable for use in the nuclear industry or other situations where the access to the pump is limited or downright impossible.

- Tesař, V.: Safe pumping of hazardous liquids—A survey of no-moving-part pump principles. Chemical Engineering Journal, 168(1) (2011) 23-34.
- Tesař, V.: Pump for extremely dangerous liquids. Chemical Engineering Research and Design, 89, 7A (2011) 940-956.
- Tesař, V.: Fluidics: the answer to problems of handling hazardous fluids. Safety and Security Engineering IV. Southampton: WIT Press, 2011, 465-477.

3D atomistic simulation of fatigue behaviour of cracks in single crystal of bcc iron

The results of 3D atomistic simulations of the fatigue behaviour of the ductile crack at 300K show that the threshold for dislocation emission and subsequent plastic growth of the ductile crack under cyclic loading in tensile mode is several times lower than the threshold for monotonic tension loading in the same mode. The results also show that for a cyclically loaded sample, the shear mode crack growth threshold of K-factor lies below the tensile mode threshold of the geometrically equal specimen.

- Uhnáková, A. – Machová, A. – Hora, P.: 3D atomistic simulation of fatigue behavior of a ductile crack in bcc iron. International Journal of Fatigue, 33 (2011) 1182-1188.
- Uhnáková, A. – Pokluda, J. – Machová, A. – Hora, P.: 3D atomistic simulation of fatigue behaviour of cracked single crystal of bcc iron loaded in mode III. International Journal of Fatigue, 33 (2011) 1564-1573.

Mathematical modeling of martensitic microstructures

Within a frame of broad international collaboration (Aalto University of Technology, Finland; Adaptamat Ltd., Finland; IFW Dresden, Germany) and in collaboration with the Institute of Physics CAS a detailed analysis of microstructures of 10M-modulated martensite in Ni2MnGa shape memory ally was conducted. The results have shown that the different mobility of twins in this alloy is caused by the difference between the twinning systems of the twins. Simultaneously, calculations of elastic strains in weakly incompatible microstructures of the Cu-Al-Ni alloy were performed with the emphasis on the strain fields and the micromorphology of the twinned-to-detwinned interfaces appearing between the single variant of martensite and the first order laminate of the alloy. The results of mathematical modelling of martensitic microstructures are important for the interpretation of experimental observations in the shape-memory materials.

- Straka, L. - Heczko, O. - Seiner, H. - Lanska, N. - Drahokoupil, J. - Soroka, A.- Fahler, S. - Hanninen, H. – Sozinov, A.: Highly mobile twinned interface in 10 M modulated Ni–Mn–Ga martensite: Analysis beyond the tetragonal approximation of lattice. Acta Materialia, 59 (2011), 7450–7463.
- Seiner, H. - Glatz, O. – Landa, M.: A finite element analysis of the morphology of the twinned-to-detwinned interface observed in microstructure of the Cu–Al–Ni shape memory alloy. International Journal of Solids and Structures, 48 (2011) 2005–201.

2012

Unique ultrasonic methods for investigation of the mechanical properties of solids and modern materials

The non-contact resonant ultrasound spectroscopy (RUS) method was combined with the ultrasonic vibration modal analysis of small material samples and an advanced methodology for the solution of the inverse problem of determining the elasticity and evaluation of damping depending on the temperature and possibly on the external (magnetic) field. Such findings on the link between microstructure groups of materials, their mechanical and other physical properties would not be possible to obtain without the newly developed experimental methods.

By combination of various ultrasonic methods the elastic moduli of a single crystal of dysprosium scandate (DyScO3) were determined. DyScO3 is widely used as a substrate for growth of thin single crystal ferroelectric layers. For this reason it is necessary to know its anisotropic bending stiffness, which enables us to calculate the elastic interaction between the substrate and the layer.

The designed generalization of the RUS method for the determination of the elastic moduli of homogeneous samples of materials also enables us to measure samples with a linear gradient of material properties, the so-called functionally graded materials, e.g. ceramic materials. This modification utilizes the fact that the gradient creates asymmetry in the modal shapes of the eigenvibrations of the sample.

The RUS method was used to study magneto-elasticity and magneto-plasticity of all the three phases of the Ni2MnGa alloy: austenite, premartensite (high-temperature phases) and martensite (low-temperature phase). For the high-temperature phases, the coupling between the magnetic microstructure and elasticity was studied and for the low temperature phase the mobility of the interfaces during the magnetically induced pseudoplasticity was studied.

- Janovská, M. - Sedlák, P. - Seiner, H. - Landa, M. - Marton, P. - Ondrejkovič, P. - Hlinka, J.: Anisotropic elasticity of DyScO3 substrates. Journal of Physics-Condensed Matter, 24(38) (2012) 1-8, art. no. 385404.
- Seiner, H. – Sedlák, P. - Bodnárová, L. - Kruisová, A. - Landa, M. - De Pablos, A. - Belmonte, M. Sensitivity of the resonant ultrasound spectroscopy to weak gradients of elastic properties. Journal of the Acoustical Society of America, 131(5) (2012) 3775–3785.

- Heczko, O. - Seiner, H. - Sedlák, P. - Kopeček, J. - Landa, M.: Anomalous lattice softening of Ni2MnGa austenite due to magnetoelastic coupling. Journal of Applied Physics, 111(7) (2012), art. no. 07A929, p. 3.
- Straka, L. - Soroka, A. - Seiner, H. - Hänninen, H. - Sozinov, A.: Temperature dependence of twinning stress of Type i and Type II twins in 10M modulated Ni-Mn-Ga martensite. Scripta Materialia, 67 (2012) 25-28.

New principle of measurement of composition of two-phase mixtures

The results feature two levels of significance. The first level is science popularization and a demonstration of the fact that experimental fluid mechanics and thermodynamics are not enclosed in sophisticated laboratories only, but their manifestation is evident in a daily life. A „kitchen experiment" during preparation of a coffee is demonstrated. The submerged teaspoon is used to tap the bottom of the mug. One can hear a tone that slowly rises in pitch. The tone is generated by a standing wave in the liquid, similarly as tones in musical instruments (flute, organ) are generated in air. While the tone in air is constant at a given temperature, the tone of coffee slowly rises in pitch, because the speed of sound increases as the bubbles disappear. Another „kitchen experiment" demonstrates an inverse effect, when hot tap water is poured into a mug and the tapping starts. First, the tone lowers in pitch, followed by the increase found in the first experiment.

The relatively simple experiment can be interpreted and quantified, revealing some novel findings. The sound recording has been analyzed using time-frequency signal processing. The theory describes the dynamics and the reasons behind the process, namely the nonlinear dependence of the speed of sound in a gas/liquid mixture on the volume fraction of the bubbles, and the nonlinear time dependences.

The described sound effect can find its application in laboratories and in industry, e.g. for the contactless measurement of composition two-phase mixtures. Therefore, a third experiment was performed with an arrangement corresponding to vacuum degasification, a typical procedure in process engineering. A clearly distinguishable 6.3 octaves decrease of the tone pitch was found.

- Trávníček, Z. - Fedorchenko, A.I. - Pavelka, M. - Hrubý, J.: Visualization of the hot chocolate sound effect by spectrograms. Journal of Sound and Vibration, 331(25) (2012) 5387-5392.

Computer simulations of airflow in oscillating human vocal folds

Flow induced vibrations of human vocal folds were numerically simulated by the finite-element method used for the solution of the incompressible Navier-Stokes equations. The developed method enabled modelling of conditions for the phonation onset given by the so-called phonation threshold pressure in the human lungs or by a minimum of the required airflow rate from trachea. Large vibration amplitudes of the vocal folds were accommodated by a movable computational grid using the Arbitrary Langrangian-Eulerian method and each self-oscillating vocal fold was modelled by an equivalent simplified dynamic system strongly coupled with the airflow.

Original results of the computer simulations were also obtained for a model of compressible flow and the 3D simulations of the airflow in the vibrating glottis analyzed by the finite volume method. The computations were performed on large 3D dynamic meshes with up to several millions of elements. The developed parallel CFD solver running on a computational cluster produced important information on the airflow field patterns, jet oscillations and aerodynamic loading of the oscillating vocal folds, and also enabled us to simulate the acoustic characteristics of phonation.

The results of the numerical simulations agree well with the clinical measurements of phonation onset characteristics and are important for the studies of the fundamental physical phenomena enabling the voice production. The results have a good potential for applications, for example in the development of vocal folds prosthesis after total laryngectomy.

- Sváček, P. - Horáček, J.: Numerical simulation of glottal flow in interaction with self oscillating vocal folds: Comparison of finite element approximation with simplified model. Communications in Computational Physics, 3 (2012) 789-806.
- Šidlof, P. - Horáček, J. - Řidký, V.: Parallel CFD simulation of flow in a 3D model of vibrating human vocal folds. Computers & Fluids, 2013, 80(1) 290-300.
- Pořízková P. - Kozel K. - Horáček J.: Numerical simulation of unsteady compressible flow in convergent channel: Pressure spectral analysis. Journal of Applied Mathematics, 2012, Article ID 545120, 9 pages, doi:10.1155/2012/545120.

2013

Mechanical properties of microstructures in 'smart' magnetic alloys

Smart alloys can change their shape in response to external loading and smart magnetic alloys can change their shape in response to external magnetic fields. In collaboration with the Institute of Physics CAS and the Aalto University (Finland) the microstructures in crystals of several selected alloys were analyzed (e.g. the magnetic shape-memory alloy Co-Ni-Al) and the influence of the microstructures on the mechanical and thermomechanical properties of the material was determined.

- Seiner, H. - Kopeček, J. - Sedlák, P. - Bodnárová, L. – Landa, M. – Sedmák, P. - Heczko O.: Microstructure, martensitic transformation and anomalies in c'-softening in Co–Ni–Al ferromagnetic shape memory alloys. Acta Materialia, 61 (2013) 5869–5876.
- Seiner, H. - Sedlák, P. - Bodnárová, L. - Drahokoupil J. - Kopecký, V. - Kopeček, J. – Landa, M. - Heczko O.: The effect of antiphase boundaries on the elastic properties of Ni-Mn-Ga austenite and premartensite. Journal of Physics: Condensed Matter, 25 (2013) 426402(1-10).

Theoretical and experimental modeling of generators of synthetic and hybrid synthetic jets

Synthetic jets are fluid flows generated by periodic pulsations. To enhance their parameters (flow rate, momentum) it is possible to use a suitable fluidic diode. The resulting hybrid synthetic jet increases the flow by sucking through these diodes. The problem lies in finding a suitable geometry and the resonant properties of the whole system. The research has produced five publications in renowned journals and a granted patent.

- Trávníček, Z. - Tesař, V. - Kordík, J. - Wang, A.B.- Hsu, S.S. Method for fluid input into a hybrid synthetic jet actuator and device for realizing this method. Patent No 304219, 27.11.2013.
- Tesař, V. - Kordík, J. Effective hydraulic resistance of a nozzle in an electrodynamic actuator generating hybrid-synthetic jet – Part I: Data acquisition. Sensors and Actuators A - Physical, 2013, 199, 379-390.

- Tesař, V. - Kordík, J. Effective hydraulic resistance of a nozzle in an electrodynamic actuator generating hybrid-synthetic jet – Part II: Analysis and Correlations. Sensors and Actuators A - Physical, 2013, 199, 391-400.
- Tesař, V. - Kordík, J. Two forward-flow regimes in actuator nozzles with large-amplitude pulsation. Sensors and Actuators A - Physical, 2013, 191(1) 2013, 34-44.
- Kordík, J. - Trávníček, Z. Novel Fluidic Diode for Hybrid Synthetic Jet Actuator. Journal of Fluids Engineering-Transactions of the ASME, 2013, 135(10) "101101-1-7".
- Kordík, J. - Trávníček, Z. Axisymmetric synthetic jet actuators with large streamwise dimensions, AIAA Journal. 2013, 51(12) 2862-2877.

Finite element solution of stress wave propagation problems: dispersion analysis and development of novel methods

Based on the dispersion error analysis of linear and quadratic finite elements the new recommendations for a choice of computational meshes of finite element method (FEM) were set. By the complex dispersion analysis of the B-spline FEM it was shown that the dispersion errors in the frequency spectrum decrease with the increasing number of control points and spline order. A new method of direct time integration mitigating spurious oscillations in stress and strain distributions has been derived.

- Kolman, R. - Plešek, J. - Okrouhlík, M. - Gabriel, D.: Grid dispersion analysis of plane square biquadratic serendipity finite elements in transient elastodynamics, International Journal for Numerical Methods in Engineering, 2013; 96(1) 1-28.
- Kolman, R. - Plešek, J. - Okrouhlík, M.: Complex wavenumber Fourier analysis of the B-spline based finite element method, Wave Motion, 2014, 51(2) 348-359.

Thermodynamic properties of new-generation refrigerants

Measurements of the dependence of pressure, temperature and density were performed for new-generation refrigerants, for which the investigated range was substantially broadened or which had not been studied to date. Further, the dependencies of density and surface tension on temperature at 0.1 MPa were determined. For benzene, which is a reference fluid, the surface tension was measured and a new methodology was developed for the generation of the standard reference data based on the data from various authors.

- Součková, M. – Klomfar, J. – Pátek J.: Standard reference data for the air–liquid and vapor–liquid surface tension of benzene. Fluid Phase Equilib. 2013, 356, 329– 337.
- Klomfar, J. – Součková, M. – Pátek J.: Surface Tension and p−ρ−T Data for 1,1,1,3,3-Pentafluorobutane (HFC-365mfc) and 1,1,1,2,2,3,3-Heptafluoro-3-methoxy-propane (HFE-347mcc). J. Chem. Eng. Data 2013, 58, 2316−2325.

Investigation of thermal plasma jet structure by generalized correlation dimension

The structure and dynamics of plasma is affected by non-linear turbulent phenomena, which affect many applications of plasma technology. The novel analytical method based on the generalized correlation dimension analysis takes into account the complexity of the dynamics in various regions of the flow including the turbulent areas. The most stable region was identified near the axis of the plasma jet. A short-term rotational movement in its core was identified.

- Gruber, J. - Hlína, J. - Šonský, J.: Investigations of a thermal plasma jet structure by generalized correlation dimension. J. of Physics D: Applied Physics, 46(1) (2013), 1-8.

2014

Surface tension of supercooled water: A refuted anomaly

Fascinating pictures of vegetation casted in ice and an electric traction outage in December 2014 were the consequence of an unusual rain of supercooled water (SW). SW is common in clouds. Its important property is surface tension, for which some older experimental data and theoretical results indicated an anomalous temperature dependence. Independent measurements at the Institute of Thermomechanics and at the University of West Bohemia at temperatures down to -25°C excluded such an anomaly.

- Hrubý, J. - Vinš, V. - Mareš, R. - Hykl, J. - Kalová, J. Surface Tension of Supercooled Water: No Inflection Point down to-25 degrees C. Journal of Physical Chemistry Letters. 2014, 5(3) 425-428.

Ultrasonic characterization of acoustic metamaterials

Acoustic metamaterials are solids with periodic micro- or nano-structures that are responsible for strong wave-propagation anomalies. In cooperation with the Institute of Ceramics and Glass in Madrid, an analysis of the elastic properties and the acoustic wave propagation anomalies was carried out for a periodic micro-scaffold fabricated of silicon carbide. The scaffold was studied both experimentally and by the finite-element method and it exhibited unique properties, previously not reported for any other material.

- Kruisová, A. - Seiner, H. - Sedlák, P. - Landa, M. - Román-Manso, B. - Miranzo, P. – Belmonte, M.: Acoustic metamaterial behavior of three-dimensional periodic architectures assembled by robocasting. Applied Physics Letters, 105 (2014) 211904.

Experimental and numerical investigation of friction element dissipative effects in blade shrouding

The reduction of undesirable vibrations of turbine blades damped both by the friction couplings of blades and by the friction elements in the shroud has been investigated. The interaction of the friction elements and blades was described by normal contact and friction forces. The mathematical models of the blades were based on the finite-element method and lumped rigid bodies. The dry friction forces were modeled by the modified Coulomb law. The results showed a satisfactory agreement with the experiment.

- Pešek L. - Hajžman M. - Půst L. - Zeman V. - Byrtus M. - Brůha J.: Experimental and numerical investigation of friction element dissipative effects in blade shrouding, Journal of Nonlinear Dynamics, 2015, 79(3) 1711-1726.
- Pešek, L. – Půst, L.: Blade couple connected by damping element with dry friction contacts, Journal of Theoretical and Applied Mechanics, 52(3) (2014) 815-826.

New methods for diagnostics of operational wear and suppression of instabilities in plasma torches

Plasma torches are sources of thermal plasma and they are used in a number of applications. The wear of cathode and the nozzle has a significant effect on the operational efficiency of the plasma torch. Melting, droplet formation, their expulsion and motion in the gas flow were studied by a high-speed camera and evaluated using the method of wavelet correlations. It was found that it is possible to suppress the hydrodynamic instabilities of the plasma flow by additional modulation of the arc current.

- Gruber, J. - Šonský, J. – Hlína, J.: Diagnostics of cathode material loss in cutting plasma torch. J. Phys. D: Appl. Phys. 47 (2014), 295201.
- Hlína, J. - Gruber, J. – Šonský J.: Suppression of instabilities in thermal plasma jet by additional arc current modulation. IEEE Trans. Plas. Sci., 42 (2014) 2720-2721.

Micromechanisms of formation and motion of martensitic microstructures and their experimental verification

Ferromagnetic shape-memory alloys based on the Ni-Mn-Ga system are currently intensively studied for their potential in technology applications as magnetic actuators and in micromechanics. The main feature of these materials is their ability to form oriented microstructures that can be easily controlled by external magnetic or mechanic loads. Theoretical models of such microstructures and their responses to external loads were developed and verified by a broad variety of experiments.

- Seiner, H. - Straka, L. – Heczko, O.: A microstructural model of motion of macro-twin interfaces in Ni-Mn-Ga 10M martensite. Journal of the Mechanics and Physics of Solids, 64 (2014) 198-211.
- Seiner, H. - Kopecký, V. - Landa, M. - Heczko, O.: Elasticity and magnetism of Ni2MnGa premartensitic tweed. Physica Statu Solidi B 251 (2014) 2097-2103.

Overview of investigated projects

Provider (grant agency)	**2010**	**2011**	**2012**	**2013**	**2014**
Czech Science Foundation	39 (6)*	37 (5)*	36 (6)*	28 (4)*	26 (5)*
Grant Agency of ASCR	11 (1)*	3	2	1	0
EU	2	2	0	0	0
Ministry of Industry and Trade	4	3	4	1	0
Ministry of Education Youth and Sports	6	4	5	4	5
Bilateral cooperation (ASCR)	2	2	5	4	4
Ministry of the Environment and the Pardubice region**	4	4	2	2	0
Pilot projects of the Institute	6	10	10	9	16
Technology Agency of CR	0	1	3	5	8
Ministry of the Interior	0	0	0	1	1
Total	**74**	**66**	**67**	**55**	**60**

* Postdoctoral projects, ** Environmental projects

Research Report of the team in the period 2010–2014

Institute	Institute of Thermomechanics of the CAS, v. v. i.

Scientific team	Department D 1 - Fluid Dynamics

Laboratory of Internal Flows

Documentation and analysis of 3D flow past transonic turbine blade cascade SE1050 using experimental and numerical methods (GACR project –see Appendix 3-1, No.1)

Based on experiments and numerical simulations, extent and influence of vortex structures on span-wise distributions of loss coefficient and exit flow angle has been documented and analysed at regimes with subsonic and supersonic exit velocity. Vortex structures take place within interblade channels due to development of sidewall boundary layer. Good agreement between experimental and numerical results has been achieved.

Documentation, analysis and suppression of parasitic phenomena taking place during aerodynamic tests of planar blade cascades with finite number of blades (supported by the TACR Technology Agency of the Czech Republic–see Appendix 3-1, No. 13)

Origin of parasitic structures in the outlet flow field was documented during aerodynamic measurements on a transonic blade cascade with extremely low number of blades. It was found out that these structures significantly deteriorate outlet flow field periodicity and that they influence measured parameters of the blade cascade. By thorough analysis of experimental data and results of numerical simulations, origin principle of these structures was clarified. Parasitic structures were eventually suppressed using perforated tailboard mounted in the outlet of the blade cascade.

Methodical approach to measurements of aerodynamic characteristics of supersonic turbine cascades (supported by the TACR Technology Agency of the Czech Republic –see Appendix 3-1, No. 13)

Based on theory and experiments, a methodical approach to aerodynamic measurements of supersonic turbine cascades in a high speed wind tunnel was described. Reaching supersonic velocities while the inlet and outlet flow field is kept periodic is difficult. Due to these conditions devices for shock wave cancellation has to be used. As a result of supersonic turbine tip sections being sensitive to incidence angle, inlet flow field parameters has to be set through inlet Mach number. In supersonic flow, a unique relation exists between Mach number and angle at which the flow enters a cascade. Result is also a general approach to determining high speed wind tunnel setting.

Comparison of aerodynamic characteristics of two variant root sections applied at ultra long rotor blades of large output steam turbine last stage

Based on aerodynamic experiments, comparison was made of aerodynamic characteristics of two variant root sections applied at 1375mm long rotor blades of large output steam turbine last stage. It has been shown that variant with larger number of blades in the wheel does not exhibit larger losses of kinetic energy at operation point and also thanks to larger profile curvature it can process larger pressure drop. On the other hand larger flow turning and larger angle of attack leads to narrower range of operational regimes in comparison with the variant with lower number of blades in the wheel.

Documentation and analysis of aerodynamic characteristics of midsection through the last stage rotor blading of a large output steam turbine

Aerodynamic experimental research on the flow past blade cascade representing middle profile of newly designed 1375mm long rotor blade was performed. The blade is to be applied at the last stage of low-pressure cylinder of large output steam turbine. The rotor blading consists of 60 blades. Both optical and pneumatic measurements were performed in a wide range of inlet flow angles and exit Mach numbers. Experimental results shed light on problems of transonic flow past turbine blade cascade, which was designed for large diameter of the rotor wheel.

Experimental investigation of profile flutter in aerodynamic channel

Several combinations of experimental parameters were realized during aeroelastic measurements of the self excited profile vibrations in the Mach number range M = 0.21 – 0.45. The influence of Mach number on the coupled mode flutter and stall flutter in relation to the difference between the eigenfrequencies corresponding to the translation and rotation motion of the profile was determined. Non stationary flow field was measured by interferometric method and the resulting forces and moments between the flow and vibrating profile was determined.

Laboratory of Turbulent Shear Flows

Flow control using passive and active means

The GACR project (see Appendix 3.1- No. 9) was oriented on experimental research of control of flow instabilities by means of various strategies. The instability in question was transition and separation of a boundary layer. Both active and passive control strategies were taken into account. From passive strategies: defined roughness of surface (zig-zag tape) and vortex generators (inclined fences). From active strategies: synthetic jets, steady suction/blowing and cold plasma using DBD actuator have been applied. New information on flow dynamics in separation region under/without actuation has been acquired.

Boundary layer bypass transition

An experimental investigation was carried out in transitional boundary layers on a flat plate with the setup of: zero pressure gradient (year 2012) and negative pressure gradient (years 2013 and 2014). The surface of the plate was either smooth or rough. The roughness was created by sand papers. The mean stream velocity in the experiments was set to 5, 10 and 14 m/s. Two shapes of leading edge were used. The intensity of fluctuations and dissipation length parameter were generated by means of square mesh plane grids.

The numerical simulation of transitional flows was focused on various approaches to transition modelling. Models were implemented into in house numerical codes and/or into the OpenFOAM for incompressible and compressible flows.

Secondary flow in narrow channel

Series of experiments on flow structure behind backward-facing step in a narrow channel have been performed within the GACR project (see Appendix 3.1 –No.5). The dynamics of secondary flow of second kind in channels with rectangular cross-section were studied both experimentally and numerically. The study included dynamical aspects of secondary flow generation mechanisms and interactions of secondary vortices with boundary layer, recirculation flow as well as among them. Two configurations were considered: straight narrow channel of rectangular cross-section and that with a backward-facing-step of suitable geometry. Spatiotemporal data were acquired and analysed. Thus, the experimental approach was based on application of Time-Resolved PIV method, while in mathematical modelling URANS concept was considered. Dynamical properties of the system were studied in phase space after its discretization.

Methods of analysis of spatio-temporal data

The new method of spatio-temporal data analysis has been suggested. The typical spatio-temporal data is produced by time-resolved PIV method available in the IT. The new method Oscillation Pattern Decomposition (OPD) is based on stability assessment of topological structures in the flow. The resulting modes could represent cyclostationary pseudo periodical pulsating or travelling structures, they are characterized by complex topology, single frequency and damping. The OPD method becomes to be considered as one of the standard methods for the relevant data analysis.

Basic research on isotropic homogeneous turbulence

Experiments on grid turbulence detailed analysis have been performed in S1 ONERA wind tunnel in Modane (France) within the ESWIRP project 7FP. Unique results have been obtained using several experimental methods with impact to basic theory of turbulence.

Laboratory of Environmental Aerodynamics (LEA)

During the years of 2010–2014 the Laboratory of Environmental Aerodynamics (LEA) has participated on research of atmospheric dispersion phenomena in case of application study (project of Technology Agency of the Czech Republic (TACR) (–see Appendix 3.1 – No. 19) and application researches (project of Czech Science Foundation (GACR) (see Appendix 3.1 – No. 8) and of European Cooperation in Science and Technology (COST)).

Physical and mathematical modelling of atmospheric dispersion above complex terrain

Physical and mathematical modelling of passive pollutant dispersion at atmospheric boundary layer (ABL) has been investigated for application study concerning coal dust dispersion (particulate matter lower than 10 μm) from open-pit coal mine Libouš to surrounding populated areas. For physical modelling based on similarity criteria between model and prototype, the wind-tunnel (WT) experiment has been conducted. The unique method of simultaneous point measurement of two velocity components and concentration of passive pollutant (trace gas) was performed by laser Doppler anemometry (LDA) and fast-response ionization detector (FFID). The mathematical method was based on solving of Navier-Stokes equations (NS) by means of large eddy simulation (LES). Owing to LES capability to solve the NS without Reynolds stresses parametrization down to certain magnitude of eddy structures with respect to time, the appropriate eddy structures has been obtained. The LES results has been successfully validated by WT experiment both, qualitatively (by means of mean velocity and concentration fields contours comparisons) and quantitatively (by means of mean velocity and concentration fields contours comparisons) and quantitatively (by means of validation metrics). The RANS model was therefore concluded as favoured method in case of mean velocity and concentration fields prediction with respect to computed time. However, if the detailed description of turbulent structures in conjunction of pollution turbulent fluxes is required, the LES model is more convenient.

Wind-tunnel modelling of atmospheric boundary layer above the surfaces with various degree of roughness

The influence of a surface roughness on a character of coherent phenomena in the turbulent atmospheric boundary layer (ABL) was investigated by means of the wind-tunnel modelling. Five categories of the surface roughness represented the five types of Earth’s terrain, e.g. a flat grass fields or complex urban downtown. Time-Resolved Particle Image Velocimetry (TR-PIV) used in the wind-tunnel experimental campaign provided the planar velocity data with high temporal resolution (2000 Hz). According to guideline VDI (2000), the proper scaling factor was established for each MVA and based on the higher moments we suggested a corrected depth of the ABL. The mathematical method as Proper Orthogonal Decomposition (POD) revealed that all sorts of surface roughness generate an organised structure of a similar appearance. The amount of turbulent kinetic energy (TKE) captured inside the structure increases with the increasing complexity of the surface. The Quadrant analysis showed the positive link between the roughness and the degree of coherence inside the dominant momentum flux (sweep/ejection). Finally, the Wavelet analysis confirmed that the MVA above the rougher surface exhibits the coherent motion more often and with a well-defined frequency. To date the collaboration with MFF in order to model the turbulent structures mathematically was established.

Impact of building height variation on street canyon ventilation – combination of numerical and experimental approach

A wind tunnel experiment and a large eddy simulation (LES) were used to evaluate an influence of building height variation on pollution ventilation intensity. A model of an idealised urban area was designed for this study. Vertical advective and turbulent pollution fluxes were computed from the measured data as ventilation characteristics in a focused domain. Wind tunnel and LES data were qualitatively compared with a good agreement of obtained results. A domination of advective pollution transport within the domain was determined. Turbulent pollution transport was less intensive. However, turbulent transport was significant and had opposite direction to the advective one. We found out an important role of higher buildings that caused intensive vertical pollution transport from the canyons along their leeward walls.

Quadrant analysis of the street canyon flow

Spatial Quadrant analysis investigates the spatial distribution of the sweep and ejection events which are the major contributors to the total momentum flux. The spatial analysis determines the compactness and spatial dimension of the events.

It was revealed that the sweep and ejection represent up to 90% of the total momentum flux and 80-90% of total TKE inside the street canyon. They both events pass the street canyon in alternating fashion, so their mutual correlation coefficient reaches value of -0.9.

POD (Proper Orthogonal Decomposition) analysis of a turbulent flow

The POD easily detects the organised structures in the complex flow. Dynamics of the flow is decomposed into the simpler modes with high amount of TKE (turbulent kinetic energy) inside an organised motion. Each mode captures significant dynamics (vortex, sweep/ejection, and so on). By the superposition of the modes, the original flow field can be reconstructed. By using only a limited number of modes, we can reduce the complexity of the system to the desired value. The typical scenario of the flow dynamics was evaluated. The area driving the formation of the particular mode was established

Laboratory of Computational Fluid Dynamics

Development of mathematical models for transonic flow in turbomachinery applications

The gamma - zeta model of transition to turbulence was implemented into a compressible Navier-Stokes implicit finite volume solver together with the EARSM turbulence model in 3D and tested on the transonic flow in the SE1050 turbine cascade. The non-reflecting boundary conditions for supersonic inlet were developed and tested in the frame work of finite volume method on turbine cascades.

The model of flow of condensing steam at conditions corresponding to working conditions of steam turbines in a power plant was successfully implemented. The phase changes are governed by nucleation and droplet growth models. The real properties of steam were included in the form of internationally recognized IAPWS tables. The recently developed "CFD" formulation (J. Hruby from Institute of Thermomechanics) was also included.

The coupled pressure and temperature correction algorithm and k-kL-omega turbulence model were implemented into OpenFOAM.

Development of mathematical models for incompressible flow in environmental applications

The work concerning incompressible flows included simulation of 3D turbulent flow past backward facing step and comparison with 3D PIV experimental data. The problem of numeric boundary condition for pressure in the artificial compressibility method was further studied in cases of 3D flows through bent channels. The extrapolation in the outlet based on do-nothing condition idea appeared to be essential for good convergence to steady state in the case of 180 degree bent channel.

The scheme for numeric solution of incompressible Navier-Stokes equations coupled with equation for temperature through temperature dependent viscosity and thermal conductivity was designed and used in combination with the spectral element method to the 2D calculations of flow around heated cylinder. High order ($p = 49$) polynomial approximation was used with the decomposition of the whole domain to only 9 elements. The resulting data coincide well with experiment and show the potential of high order approximation.

A parallel solver for 2D incompressible flow using finite element method in combination with multigrid based on Vanka-type smoothers was further developed and the results were compared for CPU and GPU implementation on two test cases.

Numerical simulation of turbulent flows in channels with one-sided diffuser

The numerical simulation of incompressible turbulent flows in rectangular channels with one-sided expansion was carried out for various types of backward-facing inclined steps. The abrupt enlargement of the cross-section leads to the extensive flow separation and to the considerable increase of energy losses. The numerical solution of averaged Navier-Stokes equations closed by the non-linear explicit algebraic Reynolds stress model and/or by the linear turbulence model with turbulent viscosity was accomplished partly by the finite-volume method and partly by the finite-element method. Both numerical models were compared with experimental data for flows over backward-facing steps with various inclination and/or roundness of the step. In addition to flows in wide channels, the three-dimensional turbulent flow in very narrow channels was simulated. The comparison with experimental data measured by the PIV method shows that numerical results obtained by the non-linear model of Reynolds stresses adequately describe the region of the separated flow including the secondary vortices in the channel corners behind the separation.

Research Report of the team in the period 2010–2014

Institute	Institute of Thermomechanics of the CAS, v. v. i.

Scientific team	Department D 2 –Thermodynamics

The research in the Department of thermodynamics concerns various aspects of heat and mass transfer, fluid flow, material properties, phase transitions, and various complex processes requiring specialized, mostly self-designed, experimental apparatuses, thorough theoretical understanding and expertise in mathematical modeling. In the evaluated period, the research activities were primarily concentrated in three laboratories: the Laboratory of Thermophysical Properties of Fluids (head Dr. Jaroslav Pátek), the Laboratory of Heat and Mass Transfer (head Dr. Zdeněk Trávníček), and the Laboratory of Phase Transition Kinetics (head Dr. Václav Vinš). Fourth laboratory, the Laboratory of Biological Fluids, did not perform significant experimental research due to the inactivity of its head (Dr. J. Pražák, now retired), but generated some interesting modeling output. Besides the laboratory heads, the team had several outstanding personalities – Prof. František Maršík (former department head), Prof. Václav Tesař, Prof. Tomáš Roubíček, Dr. Alexander Fedorchenko, Dr. Jan Hrubý – who were loosely connected with the laboratories and performed their research individually or with small ad hoc groups crossing the borders of the laboratories.

This report represents only a narrow selection from the output of the team. In the evaluated period, the Department of Thermodynamics generated, besides applied results, 118 articles in renowned journals and 9 patents covering a broad range of equilibrium and non-equilibrium thermodynamics, heat and mass transfer, fluid flow, and other engineering science disciplines.

The research in the **Laboratory of Thermophysicial Properties of Fluids (LTPF)** focused on thermophysical properties of alternative environmentally safe refrigerants and of ionic liquids. Ionic liquids are currently subject of intense research efforts because of their remarkable potential for applications coupled with favorable environmental properties. Two experimental facilities were used: (i) a constant volume apparatus to measure pressure-volume-temperature (PVT) relations of liquids, (ii) a tensiometer to measure the volume-temperature (VT) relation at atmospheric pressure by the buoyancy method and the surface tension-temperature relation by Wilhelmy plate and du Noüy ring method.

The constant volume apparatus, designed in the LTPF, has several unique features: it makes possible measurements at temperatures down to -90 ºC, the temperature of the sample can be defined and measured with the accuracy of 0.005 of K, the relative expanded combined uncertainty at 95% confidence level of the resultant density is 0.1%. The measurements are typically conducted in the temperature interval form 200 to 353 K and from 0.1 to 60 MPa in pressures.

In the years 2010-2013, the research was focused on the fourth generation refrigerants defined by attention to global warming (project #28 in the nomenclature of document 3-1). Experimental data on *PVT* relation were obtained for 9 alternative refrigerants with applications in the field of refrigeration and heat pumps [5,6]. Based on the obtained data, a mathematical formulation of thermodynamic properties was developed in the form of the Helmholtz free energy for all studied refrigerants.

For 13 still poorly studied ionic liquids, their surface tension was measured and for 16 ionic liquids the temperature dependence of their VT-relation at 0.1 MPa, most often at temperatures from 263 to 353 K [1]. The focus on ionic liquids was based on the fact that ecologically motivated innovations in the field of refrigeration do not consist only in the introduction of alternative refrigerants for compressor systems, but possible use of alternative approaches, especially absorption refrigeration, is investigated with the use of ionic liquids as absorbent. Models were developed of the dependence of the studied properties of ionic liquids on the anion and cation structure [3]. Ionic liquids have been studied with alkyl imidazolium-, pyridinium-, pyrrolidinium-, piperidinium, and phosphonium-based cation and with trifluoro- methanesulfonate, tetrafluoroborate, bis(trifluoromethylsulfonyl)imide, dicyanamide, tris-(pentafluoroethyl)trifluorophosphate and iodide anion. The results obtained during the years from 2010 to 2013 have been published in 11 papers in impacted journals.

Within a new five-year project (#39), in the years 2013-2014, the research was focused on ionic liquids. The *PVT* relation at temperatures from 218 K to 364 K was obtained for five ionic liquids and for three of them it has already been published [4]. Measurements of the surface tension-temperature and *VT* relation were performed for 9 and 14 ionic liquids, respectively. Our constant volume *PVT* data are the only ones available in the temperature region below 273 K. This temperature region forms a specific part of the liquid range of ionic liquids, which has its own importance in applications such as the low temperature heat transfer medium and electrolyte, refrigeration, and low temperature tribological or hydraulic applications. Comprehensive property data are required not only for concrete applications, but they also form a fundamental knowledge base for further processing as the development of predictive schemes, formulations of thermodynamic properties and theoretical modeling.

Experimental data on the properties of ionic liquids are often scarce, not sufficiently accurate, or even absent. For molar volumes at the pressure of 0.1 MPa and the surface tension we have developed a group contribution approach to extract more reliable values of the properties by examining the data within the context of the entire classes of related substances within one or several homologous series of ionic liquids. The structure property models are used to identify the most reliable values for the investigated properties through the intercomparison of the data for various ionic liquids from a comprehensive database and through determination of the conformity of the individual data sets with the proposed group contribution concept. The aim was not to develop a predictive model covering as many as possible ionic liquids at the price of low accuracy, but a model providing reliable property values, which can be considered as the standard reference ones. To this purpose, an original method [2] was developed to identify data sets of the highest quality, contained in a sufficiently comprehensive body of experimental data obtained by great number of authors using a number of different methods. We have shown that the group contribution models are able to describe the density data for ionic liquids, which share a homologous series of cations, within the uncertainty of the experimental data.

All the reported results were achieved exclusively by LTPF staff. They were published in 16 papers in high-impact journals which have been 152 times cited up to now.

An important field of study in the **Laboratory of Heat and Mass Transfer (LHMT)** were synthetic jets. A synthetic jet (SJ) is a fluid flow generated by pushing and pulling fluid from a cavity through an orifice or a nozzle. The cavity is typically bounded at one end by a rigid wall with an emitting orifice and at the other end by an actuating surface (a diaphragm or piston top). The flow in the orifice reverses its direction after each stroke while the time-mean mass flux in the orifice is zero. SJ offers potential advantages for various applications of active control of flow/thermal fields such as heat/mass transfer applications (drying technologies or cooling of highly loaded electronic devices or gas turbine blades). Paper [7] proposed an axisymmetric air jet, which is excited using a SJ system. Flow visualization, hot-wire anemometry, PIV, and naphthalene sublimation techniques were used. The effects of the Strouhal number and orifice-to-wall spacing on a distribution of the local heat transfer rate were evaluated. The most significant effects were found under small orifice-to-wall spacing. The excitation led to heat transfer increase in the stagnation area – the most prominent enhancement 40% was found at the stagnation point. Recently, novel methods of evaluation of SJ velocity have been proposed [9]. These methods are based on the measurement of an actuator electrical input (alternating current and voltage) and are applicable for loudspeaker-based actuators with air as the working fluid. Paper [9] follows a long-term cooperation between LHMT and the Technical University of Liberec (TUL). Main part of the study was performed at LMHT. An experimental validation of the proposed methods was performed by means of the laser Doppler vibrometry at TUL. Further results relevant to the nonsteady flow/thermal field and their control have been published in 8 articles in reputable journals.

Paper [14] is an important representative of series of papers in which experimental data accumulated by Dr. Kordík on a laboratory model of axisymmetric SJ were processed based on the underlying idea the Tesař's similarity solution of jets with turbulence modelled by two-equation isotropic fluctuation model. Unusual feature is variation of parameters (called "constants" in the classical similarity transformation) along the jet axis. Interestingly, this variation is non-monotonous: there is an abrupt change in the character at a certain distance from the nozzle which was found to indicate a transition of organized vortices into the turbulent chaos. In a search for a rule governing this transition, vortices in the organized part of the SJs were modelled as spherical objects. It was discovered that in a wide range of various SJs - of Stokes number values from Sk = 11.5 to 108.8 (corresponding to frequencies from ~10 Hz to ~100 Hz), the transition occurs at the axial distance from the nozzle equal to ~10 diameters of these model objects.

A hybrid synthetic jet (HSJ) is an advanced variant of the SJ. HSJ actuators were proposed and developed in our laboratory. The most investigated variant consists of a common SJ actuator and a reciprocating pump with valve-less rectification. In contrast to standard SJs, hybrid SJs are intrinsically non-zero-net-mass-flux jets. This enhances the produced momentum rate, which is desirable for application. An advanced variant of the HSJ actuator, operating in a double-acting regime, were patented [27]. The device was intended for cooling of a heated body. Patent [27] follows a previous long-term research collaboration between LHMT and the group of Prof. A. B. Wang at the National Taiwan University (NTU). Other 4 recent results dealing with HSJ has been published in renowned journals and a Czech patent has been awarded. The research of SJs and HSJs was supported by grants #23 and #31.

Vortex shedding under nonisothermal condition is another topic of research which is systematically performed by LHMT in cooperation with the A. B. Wang at NTU. Since the time of Prof. V. Strouhal at the end of 19th century, the phenomenon of vortex shedding from a bluff body has been studied by many authors. The phenomenon is important for theoretical study of hydrodynamic instability and it is also important from the engineering point of view as one of the sources of the flow-induced vibrations, noise, or even a body collapse. It influences the drag as well as heat transfer in external flow. Recent paper [8] extended the knowledge towards wake flow behind cooled bluff bodies. The first part of the study was performed at LHMT (task formulation, flow visualization and preliminary quantification). The final experiments were performed at NTU using a very-low-speed non-isothermal wind tunnel not available in the CR. The results confirmed that cylinder cooling destabilizes the wake flow in air, i.e., the laminar steady regime can be changed into the vortex shedding regime, and the vortex shedding frequency increases as the cylinder temperature decreases. This thermal effect is consistent with its counterpart, the known effect of air-flow stabilization by cylinder heating. The effective temperature and effective Reynolds number concept have been confirmed. Besides paper [8], further 3 articles relevant to this topic have been published in renowned journals. The research was supported by project #42 and by the Czech-Taiwanese Project Based Personnel Exchange program (PPP project MOST/14/001).

Further research at LHMT concerned acoustic effects in thermal or flow fields. Sound propagation in two-phase fluids has been investigated for the popular case of the “hot chocolate sound” [10] showing that a relatively simple experiment can be interpreted and quantified, revealing novel findings, potentially applicable, e.g., for contactless composition measurements. A thermoacoustic engine, namely a standing-wave thermoacoustic prime mover with a quarter-wave resonator, has been investigated [32] in collaboration of LHMT (problem formulation, experiment design, theoretical analysis) with TUL (optical and thermo-anemometric measurements) and NTU (problem formulation). The results have confirmed a proper function of the prime mover and advantages of the developed optical setup based on a Michelson interferometer. The research was supported by the bilateral Czech-Taiwanese project #36.

Patents [28] and [30] and papers [11], [12], [13] contain some of the results obtained in an effort to generate very small gas bubbles in a liquid, which are needed in a wide number of branches of process engineering. The most important among them is production of renewable automobile fuels from primitive plants – algae. They can increase their biomass by photosynthesis (doubling each 3.5 hours) needing only sunshine, water and CO2. The latter is available in air transferred to the algae in bubbles. The smaller are the bubbles, the higher is effectiveness of the transfer. Previously known methods of formation of microbubbles are energetically ineffective. Discovery by Tesař and Zimmerman of the efficient method based on applying oscillation in the air supply dramatically changed the scenario. It was discovered that the problem is in the conjunction growth of microbubbles [13]. New fluidic oscillators according to the patents listed above are very simple (have no moving parts) and quite inexpensive. Together with progress in other steps of algae processing, there is a real perspective of decreased importance of present-day fuels from fossil sources imported from politically unstable regions. Research of efficient microbubble generation was supported by projects #40 and #45.

A study supported by project #46 focused on potential applications in analytical micro-electro-mechanical devices (MEMS). It has been shown that a vibrating nanotube in cantilever and bridge configurations can be used as ultrasensitive mass sensor [15] and a miniature viscosity sensor based on a vibrating optical fiber, employing optical bend loss for motion detection was developed. The work has been done primarily by LHMT members with contribution of Y.-L. Chen of the Academia Sinica, Taiwan, as doctoral advisor of the first author.

Research team of the **Laboratory of Phase Transition Kinetics** (LPTK, http://www.it.cas.cz/en/d2/l022) consists of two senior researchers, four junior researchers, three postdocs, and two doctoral students and one master-degree student. Main research activities of the LPTK team are connected with theoretical and experimental investigation of the thermophysical properties of metastable fluids, phase transitions, particularly nucleation of droplets and bubbles. Several LPTK researchers are active members of the International Association for Properties of Water and Steam (IAPWS, http://www.iapws.org/) and much of the research at LPTK is motivated by the needs of IAPWS. The participation in IAPWS was supported by travel grants #44 and #48.

During the reported period, a large part of the experimental work at LPTK was focused on investigation of thermophysical properties of pure water under the metastable supercooled liquid conditions. Two in-house designed apparatuses have been developed for measurement of surface tension and density of supercooled water. The surface tension of supercooled water was successfully determined at temperatures down to –25°C [16]. The data from LPTK were in mutual agreement with the independent results obtained on another apparatus developed in cooperation with the University of West Bohemia in Pilsen. The new data were used to validate extrapolation of the IAPWS correlation for the surface tension of ordinary water to subzero temperatures. The correlation of the surface tension of supercooled water is of a high importance, especially, in atmospheric research. The apparatus for measurement of the density of supercooled water has been designed, manufactured, and tested during the reporting period. The setup allows measurement at temperatures down to –50°C and pressures up to 200 MPa. Preliminary data for the density of supercooled water at pressures up to 40 MPa and temperatures down to –20°C were obtained during 2014. Research on the supercooled water was supported mainly by projects #24 and #37.

Further research activities, supported by projects #30 and #35, were motivated by the need of accurate modeling of non-equilibrium condensation in steam turbines. An analytical formulation for steam suitable for computational fluid dynamics (CFD) has been developed [19]. Unlike common accurate equations of state given in terms of the Helmholtz function or the Gibbs function, the new formulation defined in terms of entropy allows to consider mass density and specific internal energy as independent variables, i.e. two most important variables for effective CFD calculations. This approach allows accurate and fully consistent representation of real steam properties with little computation costs, particularly avoiding iteration. Experimental research of the condensation in steam turbines involved development of special expansion chambers for condensation studies and a patented sampling loop [29] allowing, using passive control elements, a continuous dilution of a sample withdrawn from a condensing environment in a fixed mixing ratio independently on the pressure and temperature fluctuations of the environment. The nucleation of water droplets was also investigated in frame of a long-term collaboration with the group of Prof. D. Smeulders at the Eindhoven University of Technology [20]. The contribution of

LKPT was primarily in the modeling of the gas effect on the bulk and interfacial thermodynamics of nucleating droplets.

Nucleation was also investigated for non-aqueous systems with help of the classical nucleation theory (CNT) and the density gradient theory (DGT) combined with the SAFT type equation of state [31]. CNT was modified in order to improve predictions of bubble formation in alkane systems [17]. Various theoretical approaches to nucleation of droplets and bubbles were supported by projects #22, #32, #35 and #37.

A thermodynamic model for CO_2 clathrates (gas hydrates) based on the van der Waals and Platteeuw theory was developed in close cooperation between the LPTK members and the group of prof. Roland Span from the Ruhr-University Bochum [18]. The model has recently been implemented in TREND 2.0 (Thermodynamic Reference & Engineering Data) software package which uses highly-accurate equations of state for modeling thermophysical properties and phase equilibria of large variety of systems relevant especially for CCS and LNG applications. The collaboration on modeling of gas hydrates was supported by the Young Scientist IAPWS Project, and project #51.

Besides the investigation of the properties of fluid systems, numerous mathematical models in continuum mechanics and thermomechanics of solids have been developed. These models are generally described by systems of nonlinear partial differential equations or inequalities formulated in a thermodynamically consistent way and mathematically analysed with the aim to prove rigorously existence of their solutions and devise efficient numerical strategies for their approximation implementable on computers. Examples are models in geophysics [23,24] or in phase transformations in ferroic materials [25,26]. Other examples can be plasticity, damage, or adhesive contacts formulated either in small or in large strains. Certain attention has been paid to various activated, primarily rate-independent processes. This research activity have been performed within the grant project #33 and has eventually been summarized in the monograph A. Mielke, T. Roubíček: Rate-Independent Systems - Theory and Application. (Springer, currently in print).

The experimental work in the Laboratory of Biological Fluids ceased in consequence of inactivity and retirement of the laboratory head Dr. Pražák and with respect to different plans for the future. Nevertheless, significant results have been achieved in theoretical modeling of bone remodeling [22,33], which is a fundamental biological process that controls bone microrepair, adaptation to environmental loads and calcium regulation among other important processes. We elaborated a new model that combines most of these essential aspects in bone remodelling with especial focus on the effect of the mechanical environment into the biochemical control of bone adaptation mainly associated to the well-known RANKL-RANK-OPG pathway. The bone is treated as a self-organizing system capable of exchanging matter, energy, and entropy with its surroundings. Unlike previous models in which mechanical loading is regarded as the only stimulus for bone remodelling, the present model establishes a unique coupling between mechanical loading and the chemical reactions involved in the process of bone remodelling. This model was incorporated into the finite element software ANSYS to compute density distribution in distal femoral bone both before and after total knee arthoplasty. The predicted results show a good correspondence with experimental and clinical findings. Also in focus was modeling of the cardio vascular system. The mixed formulation of the finite element method with the separately interpolated pressure was used. The coupling of structure and fluid models allowed simulation of self-induced large deflection oscillations of blood vessels. The biomedicine research was supported by project #26.

Besides the above described fundamental research, the team of the Department of Thermodynamics also positively responded to challenges from the industry. Co-financed by Technology Agency of the Czech Republic was project #45 (according to nomenclature of document 3-1) in which the method of microbubble generation using fluidic oscillation was applied to biogas and wastewater treatments, project #47 concerning the development of a hydraulic damper without idle periods, project #49 concerning heat transfer, fluid dynamics, and structure dynamics aspects of development of high-speed planetary gears. Further, 9 direct contracts have been accomplished, e.g., contract #39 (according to the nomenclature of document 3-2) considered various mass transfer phenomena determining the persistence of warfare agents, contract #43 focused on the application of fluidic oscillation tor extraction of from biomaterials, contract #44 was dedicated to an innovative design and modeling of a centrifugal spray singlet oxygen generator for a very high power chemical laser, developed by the Institute of Physics CAS with Lastec Delhi, India.

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Research Report of the team in the period 2010–2014

Institute	Institute of Thermomechanics of the CAS, v. v. i.

Scientific team	Department D3 – Dynamics and Vibration

The main scope of the department covers dynamics of basic theoretical, numerical and experimental studies on vibration of mechanical systems, identification and vibrodiagnostics of complicated and non-linear dynamic systems, and on fluid – structure interaction problems including vibroacoustics.. The department consists of three laboratories :
Laboratory of Modelling and Identification of Dynamic and Mechatronic Systems (head J. Kozánek),
Laboratory of Laboratory of Vibrodiagnostics and Nonlinear Dynamics (head L.Pešek),
Laboratory of Modelling of Multiphysical Problems (head V.Radolf).

The experimental research of these laboratories is carried out in the **Experimental Laboratory of Department D3.**

Summary of the team outputs:
Articles in IF journals : 35
Articles in other journals : 54
Books : 2
Chapters in books : 7
Contributions in the conference text-books : 197
Applied results: 25
Research Projects : 10 GACR (CSF), 1 TACR, 1 MEYS
Research Contracts: 23
Collaborative Contracts : 1

Laboratory of Modelling and Identification of Dynamic and Mechatronic Systems

The Laboratory of Modelling and Identification of Dynamic and Mechatronic Systems is engaged in the identification and tuning of complicated and mechatronic dynamical systems, the development of mathematical and physical modelling methods for these systems, and their optimisation. The mathematical models are considered either linear with the corresponding spectral and modal characteristics or weak and stronger nonlinear. Applications are found in the dynamics of machines with an emphasis on rotational machines with both classic and contactless bearings (no.61 in the List of grants) and various physical fundamentals, e.g. modelling and stability of airfoils (no.55, 59 in the List of grants).
In recent years, the following specific scientific problems were solved:

The spectral properties and identification of aerostatic bearings were the subject of research that is published in the paper of Acta Mechanica Sinica (2011). Mathematical model of these bearings was identified with the help of harmonic force excitation independently from the speed of journal rotation. The stiffness and damping matrices were identified for different air inlet pressures. The calculated spectral properties allow to determine the stability boundary of the system.

The limitation of the lateral vibration of rotors with rolling-element bearings passing through critical speeds is possible by means of tuning the stiffness of the system supports. Newmark method has been proposed and tested for solution of the equations of motion in the paper of Mechanism and Machine Theory (2011).

The vibration amplitudes of a rigid rotor damped by magnetorheological squeeze film dampers and magnitude of the force transmitted to the stationary part during the steady state operating regime, were investigated. To achieve the optimum performance of the rotor in a wide range of angular velocities and when passing through the critical speeds the damping effect must be controllable. For this purpose, the application of semiactive magnetorheological dampers has been analysed (Smart Materials & Structures, 2012). The equations of motion of the rotor are nonlinear due to the damping forces and the Runge–Kutta integration method was applied to solve them.

The flow field acting on the fluttering profile, kinematics of the profile, aerodynamic forces and moments were investigated in the paper of International Journal of Structural Stability and Dynamics (2013). A high speed camera was used for interferometry visualization of the fluttering NACA0015 profile elastically supported in a translation and rotation. First, the mathematical model of the support of investigated profile was identified using minimum least squares differences between modeled and measured system responses. A special graphical Matlab procedure was proposed for evaluation of interferograms. Kinematic analysis defining motion of the profile as a function of time was obtained. Numerical integration of pressure functions around the airfoil surface allows calculation of the resulting aerodynamic forces and moments.

The results of the simultaneous determination of the elastic modulus and density or thickness of ultrathin films utilizing micro and nanoresonators under applied axial force were published in the paper of Journal of Applied Physics (2014). A method to simultaneously determine the elastic modulus and density or thickness of ultrathin films deposited on various substrate materials was proposed. This methodology utilizes measurement of the resonant frequencies corresponding applied axial tension. Elastic modulus and density or thickness of thin film are obtained from the ratio between the resonant frequencies of the nanoresonator with and without applied axial force. This work was supported by the Academia Sinica Career Development Award, No. 100-CD4-M01, the National Science Council of Taiwan, NSC 101-2112-M-001-003-MY3.

Laboratory of vibrodiagnostics and nonlinear dynamics

The Laboratory of Vibrodiagnostics and Nonlinear Dynamics is primarily engaged in the methods of monitoring vibrations and dynamic loading of machine elements during rotation, the vibrodiagnostics of rotating machines, the vibroacoustic properties of mechanical systems, and numerical simulations of the vibrations of nonlinear systems. Dynamic behaviour with thermo-mechanical coupling is modelled for damping elements made of thermoviscoelastic materials. The stability of motion, the regions of chaotic and irregular motions, and the nonlinear interaction of oscillating dynamical systems with a source of vibration energy and external electromechanical systems, are primarily under study in the numerical simulation of nonlinear mechanical systems.

The latest theoretical-experimental research of dynamical behavior of rotary bladed wheels (no.54 in the List of grants) was aimed at increase of the dissipation of mechanical energy by the friction couplings within bladings of modern turbine machines. The main result of the research is development of experimental and computational methods for explanation of till now neglected physical phenomena that occur in large turbo machines. The research was aimed mainly at reduction of the dynamical mechanical stress of bladed wheels by means of appropriately designed friction elements or friction surfaces of blades. At the first stage it concerned to design and build physical wheel model with several types of blade systems: a) blades linked with wedged friction element, b) twisted blades with friction couplings between blade heads and c) blades linked with the damping wire. Next dynamic behavior of the bladed wheels with inner couplings was described by analytical and finite element computational models of blade bundles and bladed wheels. These models enable by means of friction characteristics of contact surfaces qualitatively and quantitatively evaluate the influence of damping elements on deformation resonant curves and their efficiency on vibration reduction of models of blades. The modelling of contact by means of Coulomb friction model considering static and dynamic friction coefficients enabled to analyze initiation and evolution of macroslips from stick-slip contacts using time variable contact states at different dynamic regimes, such as at resonant vibration or at free vibration attenuation. The friction characteristics under different normal loads, vibration amplitudes and frequencies were ascertained experimentally.The numerical results were in good agreement with the experiment and show non-linear effect of friction couplings mainly in cases of macroslips when the vibrational damping significantly arises.

Based on our experiment the condensed mathematical model of the bladed disk using equivalent linearization of friction damping and non-linear programming was developed and applied for parameter optimization of friction element inserted into blade shroud in co-operation with West Bohemia University, Plzen.

For the excitation and active damping of the rotor blades, the multipoint electromagnetic impulse excitation was developed. The possibilities of the passive and active damping of the blade vibrations were investigated by means of the piezoelectric foils. The functional sample of electro acoustic converter capturing acoustic waves was designed and constructed for measuring macroslips in friction contacts. The functional samples of optical sensors of the tip-timing method were designed and assembled for accurate contactless measurement of circumferential displacements of vibrating blades. The temperature material characteristics of the high temperature resistant rubber of fluoride-kautchuck were identified by the new developed method. The research of the dynamic behavior of the blades coupled with these rubber elements proved a high damping influence even at temperatures around 150^0 C.

The influences of the friction effect and wheel mistuning on the dynamic behavior of bladed wheels and on the initiation of the forward and backward traveling deformation waves were studied on the analytical models, too. For the case of mistuning of the wheel the significant influence of non-proportional distribution of damping was ascertained and more accurate „spring-dry friction“ model was proposed for the vibration reduction. By analytical-numerical methods the influence of phase shifts of excitation forces of neighboring blades evoked in service by different number of stator and rotor blades. The analysis of the model with non-proportional damping caused by non-uniformly circumferential distribution of damping proven that the resonant frequencies of the wheel get higher and that optimal values of damping from resonant amplitude reduction point of view exist. By analysis of interaction of neighboring vibrational modes of this rotating bladed model disk, it was shown that due to splitting of eigenfrequencies by circumferential imperfection and due to travelling waves the number of feasible resonant peaks increases fourfold in contrast to the case of a non-rotating disk without imperfections.

The research of new methods in vibrodiagnostics of turbine blades (no.63 in List of grants) was aimed at the detection of origin of excessive blade vibration in turbomachinery, especially in low pressure steam turbine stages, as well as new methods of contactless vibration monitoring. Solving these tasks is very a important factor for the energy industry where a failure of turbomachinery due to excessive blade vibration leads to huge economic losses. Therefore, new methods have been investigated and principles of new contactless sensors for experimental research of phenomena in steam turbines have been developed. All the methods and devices have been designed with regard to the utilization in steam turbines under operating conditions.

A contactless impulse method has been developed and verified for measuring torsion of rotors and excited turbine blade vibrations under rotation. This method has been further extended to the shrouded blades, for which any previously known method could not be used. Complex nonlinear interactions between the blades arise on the turbine wheels with integral shrouds under rotation, causing excitation of oscillations of complex shapes and many simultaneous resonant frequencies. In this case, a detailed experimental research based on accurate measurement methods is especially substantial. Considerable attention has therefore been devoted to the research and development of precision sensors of blade motion. In particular, a contactless bidirectional magnetoresistive sensor of blade passage has been developed, which allows measurement of the movement of the blade tip in two axes. This is important especially for shrouded blades, where each blade may have a different waveform. The principle of the magnetoresistive sensor was extended to the adaptive sensor. This sensor adapts its parameters according to the instantaneous value of the voltage signal levels. The magnetoresistive bridge is supplied with a higher current in the active phase, which allows obtaining more favorable sensitivity values. In the passive phase, the supply current is equal zero and the sensor is deactivated, preventing thus overheating of the sensor in contact with hot steam. The final development stage is an intelligent microcomputer-controlled magnetoresistive sensor, parameters of which can be remotely controlled via the Internet or switched for each blade individually in an intelligent autonomous mode. All developed sensors and methods are protected by the "Office for the protection of intellectual property of the Czech Republic" and have been successfully tested under operating conditions in cooperation with the turbine manufacturer Doosan Škoda Power at the power stations Temelín, Prunéřov and Počerady (no. 51, 53, 55, 58, 59, 62, 63, 66 in the list Research for practice).

Dynamics of time heteronymous weakly and strongly nonlinear planetary transmission systems with kinematic couplings–gears has been investigated during the last five-year period. It concerns a study of complicated function of many parameters including the material of gears, damping properties and damping viscous properties of lubricating oil film in the gear mesh. The purpose of this theoretical preexperimental study was to deduce the methodology that makes possible to analyse the influence of all parameter variants in the area of linear and nonlinear systems with constant and time variable damping on internal dynamics. The structures with lightening holes in cog wheel discs are characterized by time variable damping in gear meshes. More precise dynamic analysis of such systems led to mathematical–physical models, whose motions were described by ordinary deterministic nonlinear time heteronymous differential equations at the application of mass discretization. The solved examples of resonance bifurcation characteristics in the gear mesh gave a comparison between two variants with lightening wheel discs and the variant with full wheel disc, i.e. two variants with time variable quadratic damping and the variant with the constant one.

Laboratory of Modelling of Multiphysical Problems

The Laboratory of Modelling of Multiphysical Problems is engaged in the development of methods for the study of problems with respect to the interaction of flowing fluids and deformable bodies and their experimental verification in aerodynamic tunnels. The vibration characteristics and stability limits of aerohydroelastic systems are studied. Attention is also given to the modelling of acoustic-structural couplings of vibrating bodies in interaction with acoustic media and the modelling of aeroelastic interactions in the biomechanics of the human voice. The source vocal soundwaves, i.e. the self-excited oscillations of the vocal cords excited by an airstream from the lungs, and the acoustic pressure modified by the frequency-modal characteristics of the human vocal tract during the phonation of vowels is modelled.

The work of the research team of the Laboratory of Modelling of Multiphysical Problems was mainly concerned with fluid-structure interaction problems in aeroelasticity and in biomechanice of human voice in the last period.

Aeroelastic airfoil problems were numerically analysed with the aid of the developed FE code and in-house computational code considering <u>incompressible viscous turbulent flow</u>. Flexibly supported two-degrees of freedom (2-DOF) airfoil in 2D flow was subjected to a sudden gust. The flow was modelled by Reynolds averaged Navier–Stokes equations (RANS) with k−ω turbulence model. The flow problem was discretized in space using the stabilized finite element (FE) method. In order to treat the time dependent inlet boundary condition the standard stabilization procedure was modified. Further, the under relaxation procedure was introduced in order to overcome the artificial instability of the coupling algorithm (no.52 and 56 in the List of grants).

Similarly the numerical simulation of the vibrating airfoil with 3-DOF which includes rotation of a flap was studied. The simulation consists of the FE solution of the RANS equations combined with Spalart-Allmaras or κ–ω turbulence models, coupled with nonlinear ordinary differential equations describing the <u>airfoil motion with large amplitudes</u>. The time-dependent computational domain and approximation on a moving grid are treated by ALE formulation of the flow equations. The developed method is used for the computation of flow-induced oscillations of the airfoil near the flutter instability, when the displacements are large, up to ±40 degrees in rotation. The results obtained by both turbulence models were compared (no.52 and 56 in the List of grants).

The simulations of <u>viscous compressible flow</u> in time dependent 2D domains occupied by the fluid was taken into account with the aid of the Arbitrary Lagrangian-Eulerian (ALE) formulation of the Navier-Stokes equations. They are discretized by the discontinuous Galerkin finite element method (DGFEM). The time discretization is based on a semi-implicit linearized scheme, which leads to the solution of a linear algebraic system on each time level. The applicability of the developed method was demonstrated by computational results obtained for the <u>flow induced</u>

airfoil vibrations and in medical applications for the airflow in glottis. The equations of motion for elastic deformations of the human vocal folds are coupled with the equations for the fluid flow by a strong coupling. The structural problem is discretized by conforming finite elements and the Newmark method (no.56 in the List of grants).

Accurate computation of highly unsteady and massively separated 3D airflow in human vocal folds during phonation requires CFD simulations on large 3D dynamic meshes. Therefore a numerical simulation was done that presents a 3D model of flow past vibrating vocal folds solved by cell-centered finite volume method. Esspeccially, the jet deflection angle, glottal velocity and pressure, drag and lift force and jet contours in glottal channel were studied (no.56 in the List of grants).

Experimental data on flow separation from a model of the human vocal folds were measured on a four times scaled silicon rubber model, where one vocal fold was fixed and the other oscillated due to fluid–structure interaction. A PIV system was used to visualize the flow fields immediately downstream of the glottis and to measure the velocity fields. From the visualizations, the position of the flow separation point was evaluated. The results indicate that the flow separation point remains close to the narrowest cross-section during most of the vocal fold vibration cycle, but moves significantly further downstream shortly prior to and after glottal closure (no.52 and 58 in the List of grants).

Phonation into a glass tube is a voice training and therapy method that leads to beneficial effect in voice production. A pilot study examined the vocal tract shape in a female subject before, during, and after phonation into a tube using computer tomography (CT). 3D FE models of the vocal tract were derived from CT images and used to study pharyngeal closure and enlarged cross-sectional areas of the oropharyngeal and oral cavities during and after the tube-phonation. FE modelling revealed an increased input accoustic inertance of the vocal tract and an increased acoustic energy radiated out of the vocal tract after the tube-phonation (no.53 and 58 in the List of grants) – collaboration with the University of Tampere, Finland.

The problem which has been solved in biomechanics of human replacements is the increasing of the human joint replacements reliability. In vivo failure of any replacement requires the realization of reoperation which is very traumatic for the patients. Currently the reliability of two joint replacements is solved. The first is total hip joint endoprosthesis with the ceramic head, the second is metallic total replacement of the trapeziometacarpal joint. The causes of in vivo fragile destructions of the ceramic heads of hip joint endoprosthesis are solved using Weibull weakest theory and the biomaterial parameters of the ceramics are obtained from the destruction tests. The input parameters in the computational modelling are principal stresses in the head during the gait and the material parameters. The stresses in the head are significantly influenced by manufacturing inaccuracies of the cone areas of the head and the stem (no.60 in the List of grants).

Experimental Laboratory of Department D3

The laboratory is equipped with multi-channel measuring apparatus B&K PULSE 14 for computer-controlled measurement of vibration and sound and experimental modal analysis, sound level meters and special microphones B&K, digital oscilloscope YOKOGAWA for recording and analyzing signals and 3D high-speed system DANTEC for optical recording and analysis of vibrations and deformations.

For the dynamic analysis of the rotary blades is the dynamic laboratory equipped with modern drive for fast start-up and torsional excitation of physical models of bladed wheels. ABB test drive consists of synchronous servo motor with a power 10.6kW, PC control frequency inverter ACSM1. For excitation of blades under rotation, excitation system based on electromagnetic pulse excitation synchronized with revolutions was developed. Vibrations of rotating bodies are measured by strain gage methods with slip ring or telemetry transmission. Contactless "tip-timing" method used for vibrodiagnostics of blades of low pressure stages of power plants has been developed, too.

For research of vibration damping control and dynamic loading of solids and structures, the laboratory is equipped with modern control system dSPACE , which is based on autonomous control unit with its own processor and the input and output peripherals . For communication and uploading management programs is the unit connected to the PC via LAN interface. The control programs are tuned and built in Matlab-Simulink environment.

For research of thermo-mechanic properties of elastomers, the laboratory owns chamber Weiss WT3-180/40 , which allows in addition to its interior space to temper the external air circulation chamber for the case of dynamic tests on specimens of larger dimensions or testing bodies clamped on test bed.

In addition, the laboratories are equipped with special equipment for testing of aeroelastic models interacting with the flow of air and models of dynamic systems under rotation including rotor blades. In the laboratory are further developed its own special sensors for measuring various mechanical quantities (displacement, pressure, force, acceleration), together with the necessary accessories and equipment for their calibration and testing.

Further research in vibrodiagnostics of turbine blades will be promoted by a new built Laboratory of rotary laser vibrometry financially supported by the Operational Programme Prague Competitiveness. The velocity of vibration of the rotating bodies will be measured by the scanning laser vibrometer completed by the derotator from POLYTEC.

Instrumentation

- Pulse, Brüel&Kjaer for multichannel measurement and analysis of noise and vibration;
- digital oscilloscopes YOKOGAWA;
- high speed camera (1000 figures/s) with correlation system Q450 DANTEC DYNAMICS for optical measurement of time variant large strains;
- climate chamber Weiss WT3-180 / 40 with a range (-50 to 200)^{0}C ;
- Infrared thermocamera MIDAS, DIAS .
- electrodynamic shakers from B & K and LDS ; power electrodynamic shaker 1,78kN , B&K 4817;
- apparatus for contact (piezoelectric, capacitive , strain gauge) and contactless (optical , radio-telemetry) vibration measurements; laser vibrometers POLYTEC;
- function generators, e.g. HP 33120A;

Research Report of the team in the period 2010–2014

Institute	Institute of Thermomechanics of the CAS, v. v. i.

Scientific team	Department D 4 - Impact and Waves in Solids

The D4 - Impact and Waves in Solids - activities cover theoretical, numerical and experimental research of dynamical processes in solids; investigation of transient and wave phenomena in solids; impact and contact problems; phenomenological description of material behaviour and experimental verification; computational methods in continuum mechanics, fracture/damage analysis, and non-destructive testing and characterization of materials and structures.

The Department D4 consists of three laboratories : Laboratory of Computational Solid Mechanics (LCM), Laboratory of Non-Destructive Testing (LNDT) and Laboratory of Material Diagnostics (LMD). The research programme of laboratories covers theoretical disciplines (theoretical and continuum mechanics, theory of wave propagation, fluid-structure interactions, parts of solids state physics, computational material science), mathematical modelling, topical numerical methods and numerical mathematics (finite element method and its modern versions, methods of molecular dynamics, solution of linear and nonlinear problems, efficient solvers, developing proprietary finite element code PMD and parallel code for molecular dynamics), and experimental methods (based on mechanical testing, acoustics, ultrasonics, optics, and complex structural health monitoring). Owing to interdisciplinary character of D4 topics ranging from physical, material science research and numerical mathematics to mechanical engineering and biomechanics, the main results will be classified into following topics including references to research outputs in Phase I (according to ASEP number), grant projects (according to form 3.1-List of grant and programme projects supported from public means from national sources, the EU sources and foreign sources in the period 2010-2014), research for practise (according to form 3.2-Research for practise and the transfer of technologies from non-public sources) and international cooperation:

Finite element and isogeometric analysis of stress wave propagation: dispersion analysis and development of novel methods for contact-impact problems; FE software PMD

Numerical modelling of wave propagation in solids has got a long-time tradition at the Department D4. The finite element method (FEM) of continuous Galerkin type has been used for advanced wave modelling. As a tool, FE software PMD (Package for Machine Design) is utilized. PMD is designed for general engineering problems in the continuum mechanics of solids. It is a proprietary code with a long, 25-year tradition, and is currently maintained by the staff of the LCM laboratory.

The dispersion analysis of linear and quadratic serendipity finite element types has been analyzed and tested in wave propagation benchmarks for which analytical solution is available (the longitudinal impact of two cylinders/plates). Based on the dispersion error analysis of bilinear and biquadratic serendipity finite elements new recommendations for a choice of FE meshes have been set. The time-spatial dispersion analysis has also been a point of interest, where the suitable time step sizes for implicit and explicit time integrations have been recommended with optimal lumped (diagonal) mass matrices. Further, a new explicit time integrator has been proposed for accurate modelling of discontinuous wave propagation in solids. The algorithm tracks, with different integration time step sizes in accordance with their different wave speeds, the propagation fronts of longitudinal and shear waves by integrating separately the element-by-element partitioned longitudinal and shear equations of motion. Simultaneously, improvement of current computational modelling of contact-impact problems in the FEM has been accomplished. An original three dimensional algorithm based on the pre-discretization bi-penalty method has been developed. As a part, new contact searching technique for the local search problems has been proposed.

By the complex dispersion analysis of the B-spline FEM called isogeometric analysis (IGA), it was shown that the dispersion errors in the frequency spectrum decrease with the increasing number of control points and spline order. A new method of direct time integration mitigating spurious oscillations in stress and strain distributions has been derived and tested.

The PMD software has been also successfully applied in stress, seismic and life-time analyses of various devices (adsorber, gas cooler, refilling water cooler, volume and boron acid charging pump, oil pump with electric servomotor, waste water pump, boron concentrate high pressure pump, sprinkler system pump and low pressure emergency refilling pump) of the nuclear power plant MOCHOVCE (Slovakia) during completion of units 3 and 4 in 2010-11.

Research outputs-ASEP ID: [347620, 395253, 424876, 342675, 334647]; **Research for practice:** [75, 80] + NPP MOCHOVCE + APPENDIX C [72, 73, 74, 78, 79, 81]; **Grant projects:** [49, 65, 66, 68, 69, 72, 77]; **International cooperation**: University of Colorado at Boulder,USA; Korea Atomic Energy Research Institute, Republic of Korea; Institute of Cybernetics at Tallinn University of Technology, Estonia, University of Maribor, Slovenia [77]

Wave phenomena in solids: analytical and semi-analytical approaches

Fatigue damage of materials is an important problem that causes at least 80% of the failures in modern engineering components. Since the mechanism of fatigue crack initiation evolves from the surface of a specimen, the use of Rayleigh waves may be an appropriate method for a damage assessment. In thin structures as propeller or turbine blades where crack initiation evolves from edges of a specimen the Rayleigh waves may have the character of so-called edge waves. The propeller blades are very often made of composite materials that are characterized by anisotropic properties. Analysis of elastic waves in anisotropic media is much more complicated than that for isotropic media. For anisotropic solids the propagation velocities of bulk waves depend greatly on the direction of propagation, so that spreading wavefronts are far from spherical or circular. On the contrary, for a fixed direction of propagation the bulk wave velocities vary depending on orientation of material axes. A similar situation could be expected in the case of Rayleigh-edge (RE) waves. The first aim of our investigations was to study the influence of principal material directions of thin orthotropic structures on RE wave velocity. Theoretical solution was grounded on the finite element analysis. Experimental solution utilized for non-contact measurements a laser vibrometer. It has been found that Rayleigh wave velocity depends significantly (as with bulk waves) on the directions of the principal material axes. The satisfactory agreement between the calculations and experimental measurements has been attained. The next step of our investigations was to generalize the previous results. By means of the analytic approach the implicit and explicit secular equations for Rayleigh waves polarized in a plane of symmetry of an anisotropic linear elastic media were derived. The derivation of these equations was based on displacement (implicit) and stress (explicit) formulations respectively. Numerical evaluations of both equations give the same values of Rayleigh wave velocities. It has been proven that the Rayleigh wave propagation exhibits no geometric dispersion. This means that the Rayleigh wave velocity is independent of frequency. In the case of orthotropic materials (thin composites) it has been confirmed that Rayleigh wave velocity depends significantly on the directions of the principal material axes. For the same material model the analytical solutions based on the implicit and explicit secular equations were compared with the finite element and experimental data that were determined earlier. It emerged that the theory was in accordance with the experiment.

Simultaneously, the analytical solution of transient in-plane vibration of a thin viscoelastic disc caused by a radial pressure load was derived. The evaluation of relations was carried out by use of a selected numerical algorithm for the inverse Laplace transform based on the FFT and ε-algorithm using multi-precision computations in Maple.

Research outputs-ASEP ID: [396734, 333232, 385578]; **Grant projects**: [64, 71]

Development of advanced computational models in phenomenological plasticity

The main scope of the research is development of models of metal plasticity with a particular focus on directional distortional hardening. The convexity of three basic directional distortional hardening models – necessary for successful FE code implementation using radial return method - was derived. These requirements appeared to be very similar (stricter for particular cases) to those necessary for thermodynamic consistence of the models.

Selected models were implemented into both research and commercial FE-codes ABAQUS and PMD in the framework of explicit integration of constitutive equations with exact tangent stiffness. Attempt of implementation with implicit integration and consistent tangent stiffness has been made; however, its complexity exceeded practical usability.

The complete development of analytical calibration of these models appeared to be possibly the greatest challenge lately. Moreover, careful investigation of directional distortional models and their behaviour in various load cases showed that previous calibration procedures based in deformed yield surface only could lead to discrepancies in pure tension-compression behaviour. Therefore, both numerical and analytical methods of calibration of material parameters of metal materials were developed – only numerical for complicated models of directional distortional hardening. The calibration procedures span both pure static and cyclic input data. In the area of cyclic plasticity, a method for calibration of the simplest directional distortional model was developed at the basis of cyclic stress-strain curve only. It was proved that directional distortional hardening represents a convenient way to correctly describe cyclic behaviour for both flat-like and extra curved cyclic curves.

In experimental investigation of directional distortional hardening, certain load cases and their sequences were designed and possibilities of their practical implementation to the experimental campaign tested in collaboration with the LMD laboratory.

Research outputs-**ASEP ID**: [341726, 379921]; **Grant projects**: [76, 78]; **International cooperation**: Northern Arizona University,USA; University of California at Davis, USA [76,78]

3D atomistic simulations by molecular dynamics in fatigue crack propagation in metallic materials

Molecular dynamics (MD) simulation of metallic atoms under conditions of cyclic loading may provide beneficial insight to the problem of fatigue failure. In materials possessing defects, fatigue has been shown to occur at the location of defects and sometimes far below the elastic limit. Much of our understanding of material properties on the macroscopic level comes from empirical data rather than an understanding of atomic interactions resulting in the properties. Designs accounting for fatigue have proven to be time consuming and expensive. MD simulation is giving a clearer understanding of the relation between atomic interaction and its effect on the macroscopic level.

The crack simulations by MD technique in 3D bcc and fcc iron crystals were considered using in-house MD codes for parallel processing in MPI and also classical single processing. Interatomic interactions in iron were described using an N-body potential of Finnis-Sinclair type. The 3D codes have been tested in perfect samples under simple uni-axial tension and thermal conditions. The simulated thermal expansion suited well with experimental data, as well as the phonon frequency spectra.

A new 3D atomistic and experimental fracture results for different crack orientation have been obtained. It was confirmed that the ductile–brittle behaviour in bcc iron is strongly influenced by the mutual orientation of the crack and the available slip systems. Further, the character of crack extension and corresponding wave patterns have been studied in the Fe–Cu system. This work was motivated by a question how a small Cu bcc precipitate changes the brittle behaviour of the crack in comparison with pure bcc iron loaded in mode I. Finally, MD simulations were also successfully applied in the investigation of fatigue crack propagation in shear modes II, III and II+III.

Research outputs-**ASEP ID**: [428179, 421102, 376703, 363795, 359601, 351027, 343457, 341700]; **Grant projects**: [68, 70]; **International cooperation**: University of California at Santa Barbara, USA

Numerical methods for solving very large FEM problems: Application of domain-decomposition methods in computational elasticity and fluid mechanics; Sparse direct solver with reordering

The efficient numerical methods for solving large linear and nonlinear problems of computational elasticity and fluid mechanics, discretized by the FEM have been developed. We studied, improved, implemented into FE code PMD and applied the Balancing Domain Decomposition by Constraints method (BDDC) as a variant of domain decompostion method. We improved the choice of coarse degrees of freedom by adaptive choice of coarse space (Adaptive

BDDC) and by increasing the number of subdomain levels (Multispace and Multilevel BDDC). Adaptive BDDC method consists in adding of coarse degrees of freedom based on estimates of condition numbers of problems on neighbouring subdomains. We suggested an algorithm for estimates of condition numbers. Multilevel BDDC is a method, when solution on coarse grid is solved using standard BDDC method recursively as a problem of N levels. Further, we aimed at conjecture of advantages of these methods and developed adaptive multilevel method called Adaptive Multilevel BDDC. This method does not have any problems with the size of the coarse problem, and is maximally scalable. The adaptive choice of constraints guarantees very good conditioning of the problem and low number of iterations.

First, we developed the BDDC method for symmetric and positive definite problems with applications to elasticity and material engineering. Then we continued to solve problems of fluid dynamics using multilevel domain decomposition techniques. These problems lead to systems, which are non-symmetric and nonlinear. We developed parallel implementations of proposed algorithms using the MPI library and obtained robust, well-scalable and computer platform independent parallel codes, which were applied to practical problems of engineering applications (stress analysis of hip joint replacement, description of fluid flow in turbine valves etc.)

Simultaneously, we developed and assessed efficient numerical methods for the direct solution of large linear and nonlinear problems arising from the application of the finite element method in structural mechanics. Direct methods are traditionally avoided in favor of iterative methods where large problems (millions or billions of unknowns) are considered. They are, however, invaluable in engineering computations due to their robustness. We aimed on minimization of the computational resources needed for the direct solution and efficient matrix data processing. We proposed numerical methods based on the minimum degree ordering, block symmetric sparse LU-decomposition, and efficient in-core matrix storage. We implemented the proposed methods into FE code PMD, using the Open MP library to parallelize critical portions of the code. The numerical solvers were verified and tested two sets of problems: small example problems to verify the results, and large real-world engineering problems to assess the implementation. We obtained fast, resource-efficient, well-scalable and platform-independent codes that can be readily used for both linear and nonlinear elastic and inelastic analysis and eigenproblem solution and transient problems. The solver has been also successfully applied in ab-initio calculations of electronic structures.

Research outputs-ASEP ID: [438700, 423788, 379792, 342831, 359432, 377130]; **Grant projects**: [67]; **Research for practice** [83, 112]; **International cooperation**: University of Colorado at Denver, USA; Viterbi, University of Southern California, USA

Acoustic emission (AE) source location and identification

Reliable identification and classification of localized AE sources are the most important and also most difficult inverse problems solved in AE monitoring. AE source location based on artificial neural networks with arrival time profiles as inputs we improved using a topology analysis while training data are generated by calculation of shortest elastic wave paths in general structures. Newly designed algorithm approximates geodetic distance in discrete points of the body represented e.g. by its photo or drawing, which substitutes parametrical description of geometrically complicated structure. Given point grid with automatically calculated paths enables generation of sufficient training data, which are not influenced by experimental errors. New algorithm improved AE source location up to the precision of transducer aperture. The method was successfully applied during fatigue loading of aircraft parts and during the failure of loaded steel beams. We designed and verified also another new concept of precise AE source localization and identification in very complex structures where the elastic wave propagation is a complicated process. Wave interactions with the body boundaries and structure often lead to substantial loss of information about an AE source. New method is based on a Time Reversal (TR) AE signal processing. AE signals, recorded by transducers relatively far from the source are considered as a multiple convolution of the source function with the Green's (wave transfer) function and sensor transfer function. The designed procedure (TR AE signal Deconvolution) is relatively simple and doesn't require any knowledge on the material and geometry of a structure. Deconvolution method also removes effects of wave dispersion and minimizes variance of AE signal parameters. With a good simulation model of elastic wave propagation in the body the method can be applied to this model without any experiments. We proposed to solve the problems of how to recognize and classify AE sources on remote, large or very complex structures (e.g. flying aircrafts or satellites) more precisely using transfer of detected signals onto a model. As a model, a real copy or precise numerical substitute of the body may be either used. The transferred signals are rebroadcast into the model with the same transducers layout, and analyzed using TR procedure. We tested the signal transfer procedure using Pen-Test (pencil lead break) at various locations on three similar aircraft wing flanges representing as original as the model. Successful experimental results showed that the similarity between the original and its model must be very good. A simple TR simulation model was designed using the computational power of graphic processor in a standard PC. Suggested AE source analysis may be effectively used for monitoring of remote or inaccessible objects.

Grant projects: [73, 79, 80]; **Research for practice** [82, 99, 98];

Diagnostics of helicopter gearbox by continuous acoustic emission (AE)

Large and complex gearboxes or rotating machinery failures often cause high financial or humanlosses. Additionally to the mostly used vibration analyzing systems, we paid attention to monitoring of high frequency continuous AE, which eliminates most of engine noise, but requires a new signal analysis approach. New procedure of continuous AE signal processing has been proposed, consisting in effective parameterization and huge AE data (2 MHz sampling) reduction with subsequent signal threshold counting in different frequency bands. As an alternative to classical spectrogram, a “combined countogram” was newly defined on the basis of signal wavelet decomposition. Developed algorithm was applied during the tests of renovated gearboxes in different helicopter "flight modes". Detected dissimilarities between the signals originating from two components of the same type proved high sensitivity of such AE methodology for detection of damages already in early stages. New method of continuous AE analysis may be used as integral part of helicopter in-flight SHM system.

Grant projects: [81]; **Research for practice**: [100]

Nondestructive evaluation and imaging of material defects with nonlinear ultrasonic spectroscopy (NEWS)

Three NEWS procedures using harmonics and intermodulation spectral analysis of a body response to defined ultrasonic excitation were tested: 1. NWMS (Nonlinear Wave Modulation Spectroscopy), 2. NLTRM (Nonlinear Time Reversal Method), and 3. SSM (Scale Subtraction Method). NEWS methods enable a more sensitive detection and evaluation of material damage. Formerly designed NEWS procedures based on harmonics growth, time reversal and intermodulation of ultrasonic signals with the growing amplitude were verified on both small and larger parts made of metals and concrete with or without crack-like defects initiated by fatigue or static loading. Several experimental systems were assembled with various numbers and types of ultrasonic transmitters and receivers. For precise pseudo-tomography mapping of defects we used experimental setup with multiplexer and 3D scannerhandling the ultrasound receiver or laser-Doppler interferometer. Also AE was monitored during the fatigue and static loading tests as a real time defect detection procedure. AE results were correlated with applied NEWS methods and a very good correspondence of defective zones revealed by both methods reflected their robustness. Theoretical study and numerical simulations have shown that a large number of time-reversal iterations can be substituted by symmetry analysis of signals (ESAM). Under assumption that nonlinear response may be approximated by 3rd order polynomial, this substitution enables simple extraction of relevant nonlinear parameter characterizing defect. Matrices of time reversed signals and their spectra are analyzed, and their nonlinear features are extracted along all wave-paths. Non-symmetry analysis of 3rd order nonlinear parameter matrices with various sensor configurations has improved defects localization and imaging. A thorough theoretical analysis of NWMS method was performed using the model of crack combining classical and hysteretic nonlinearity. General description of hysteretic response is based on amplitude and frequency ratios of two exciting waves. Method for separation classical and hysteretic nonlinearity was proposed in the model, which enables better understanding and interpretation of experimental results. We also used elaborated NEWS methodology to examine damage in various concrete parts. The amplitude dependent spectral changes of the probing ultrasonic signals were examined as on unloaded parts as during the loading of smaller concrete samples by laboratory testing machine. Experimental results showed that evaluated nonlinear parameters are even more sensitive to the damage inception than simultaneously monitored AE. Two bigger model parts of a nuclear reactor pressure vessel (RPV) cavity were also examined. Tests have shown effectiveness of NEWS methods for periodic or continuous RPV cavity inspection even when it is performed through the ionization channels buried in the concrete. The proposed methodology can be used for NPP security and lifetime enhancement.

Research outputs-**ASEP ID**: [397079, 353569, 377071]; **Grant projects**: [74, 79, 80]; **Research for practice**: [82, 102]

Structural Health Monitoring in aerospace and civil engineering supported with two ultrasonic NDT methods - AE and NEWS

Structural Health Monitoring (SHM) becomes an important technology improving reliability and safety of aeronautical and highly stressed civil structures, and supporting their effective maintenance. A system based on combination of two ultrasonic NDT methods - AE and NEWS combined with time reversal of signals (TR-NEWS) was designed and tested under realistic conditions. AE enables real-time detection and localization of initiation and progression of defects under operational stimulations, and NEWS methods provide retrieval of structural faults and complete information on AE sources. The common employment of both methods is very effective as both utilize the same piezoelectric transducers and analyzing devices. Additional generator and power amplifier is necessary for NEWS methods and they can be used also for AE calibration. The utilization of common devices reduced necessary expenses for SHM system creation. Besides the long term fatigue tests of aircraft wing flanges, where initiation and growth of cracks from rivet holes were successfully localized, the efficiency of complex SHM system was tested on the steel roof truss of industrial hall during its controlled destruction. Installed SHM system reliably detected and forewarned incoming limit state of the structure already at 60% of failure load.

Research outputs-**ASEP ID**: [397079, 353569]; **Grant projects**: [79, 80]; **Research for practice**: [82, 102]

Noninvasive ultrasonic methods in diagnostics of biological materials

NEWS methods were examined also for noninvasive diagnostics of defects inside human teeth. The main task was tomography-like imaging of cracks or other degradation signatures. A complex internal structure of the tooth was analyzed by the chirp-coded TR-NEWS procedure using acousto-optic experimental set-up. Cross-correlation techniques with deconvolution and advanced signal processing were used to localize nonlinearity signatures. Proposed dental application represents a non-contact alternative to the current echodentography techniques. Linear ultrasonic and NEWS methods were also used in combined noninvasive mechanical and ultrasonic investigation of viscoelastic and anisotropic properties of human skin in vivo as their changes sensitively reflect dermatological and also internal diseases. A small skin-loading device with built-in transmitting and receiving ultrasonic probes was used to observe elastic wave propagation changes under stepwise tensile loading and relaxation in-vivo. Ultrasonic signals of variable amplitude in the frequency range 0.1–1MHz were transmitted along the forearm of several volunteers. Linear parameters like wave velocity and attenuation were evaluated from direct propagating waves, and time reversal signal processing was used to reveal amplitude dependent spectral changes and nonlinear effects at different loading and relaxation stages. A five-element rheologic model parameters were evaluated from relaxation curves. An easily-applicable method for immediate evaluation of human skin local anisotropy was developed using a special flexible multi-directional circular probe with built-in piezoelectric elements (array) for elastic wave velocity measurement. The anisotropy was determined from directional velocities related with complex elastic modules. The method was tested on human skin tissue in vivo. Comparative tests on isotropic materials verified the system accuracy. Developed methodology is of great interest in dermatology, plastic surgery and cosmetics and utilizable also in industrial applications for anisotropy evaluation of various materials like composites, etc. The work was realized in close international cooperation supported by the French regional program 'PLET' (Ultrasonic imaging of local viscoelastic propertis of human skin) and students exchange program 'ERASMUS'.

Research outputs-**ASEP ID**: [359805, 353569]; **International cooperation**: INSA Val de Loire, Blois / University Francois Rabelaise in Tour (F), FEMTO Institute / Université de Franche-Comté, Besançon (F)

Fatigue life prediction methods for a set of multiaxial experimental data on broad-band random loading

Using of deterministic fatigue life prediction methods for multi-axial (combined axial and torsional) broad-band random load of a tubular specimen with a one-sided transversal hole was studied at the LMD laboratory. Experimental campaign was conducted for aforementioned specimens in combined axial and torsional direction with a stochastic signal with a chosen PSD of both channels. Localizations of fatigue crack initiation as well as overall lifetimes in number of load blocks till final fracture were monitored. The campaign tested and verified several methods of life prediction differing in the definition of damage parameter and application of the mean stress effect.

Research outputs-**ASEP ID**: [367378, 377375]; **Grant projects**: [75]; **Research for practice**: [77]

Research Report of the team in the period 2010–2014

Institute	Institute of Thermomechanics of the CAS, v. v. i.

Scientific team	Department D5 - Ultrasonic Methods

The main scope of the department covers mechanics of materials and transient phenomena associated with acoustic wave propagation in solids. The department consists of two laboratories :

Laboratory of ultrasonic methods (16 members, head : Michal Landa)
and **Laboratory of experimental stress analysis** (2 members, head : Jan Trnka).

Summary of the team outputs :
Articles in IF journals : 42
Articles in other journals : 9
Books : 2
Chapters in books : 1
Contributions in the conference text-books : 20
Research Projects : 82-96 /2 EC FP6, 2 GAAV (CAS) , 1 CAS, 10 GACR (CSF)/
Research Contracts : 8
Collaborative Contracts : 5

Laboratory of ultrasonic methods (LUM)

LUM deals with both experimental and theoretical research in the field of mechanics of materials. The laboratory is oriented on the utilization of physical acoustic principles for the evaluation of mechanical properties of advanced and functional materials

Main scope:

- Determination of mechanical properties of advanced materials by ultrasonic methods
- Construction of the theoretical models on the underlying microstructural phenomena
- Use of these models to explain the constitutive behaviour at the continuum level.

Studied materials:

- ferroelastics, shape memory alloys (bulk, thin films, single- and polycrystalline),
- plasma sprayed materials, rare-earth scandates,
- diamond coatings, nano-grained metals, graphene-based composites,
- multi-phase (solid-liquid) alloys, architectured materials

For this purpose, the laboratory continuously develops original ultrasonic methods mainly based on laser-ultrasonic techniques (thermo-elastic generation of ultrasound in solids and laser detections of ultrasonic vibrations) such as contactless resonant ultrasound spectroscopy, bulk and surface acoustic wave methods, guided waves, etc. The laser-based ultrasonic methods belong to key analytical instruments of the Advanced materials multidisciplinary research center (**AdMat**) supported as the Center of Excellence by Czech Science Foundation (the project 94).

Among the novel approaches for ultrasonic evaluation of material properties developed, tested and utilized by the LUM team, the **contact-less resonant ultrasound spectroscopy (RUS)** and laser-based **surface acoustic waves (SAW) techniques** are the most noteworthy.

- Evaluation of elastic properties by means of the RUS method is based on ultrasonic vibrations of small samples of a simple shape (parallelepiped, disk, cylinder); in the contact-less set-up developed at LUM, the vibrations are both generated and detected by lasers. The development of this method was mainly motivated by investigation of temperature dependences of mechanical properties of ferroelastic materials in a vicinity of their phase transformation temperatures (projects 82,84,86,88,89,93,94), but was further modified also for analysis of mechanical properties (elasticity and internal friction) of structural materials (projects 88,92,94). The used approach for evaluation for elasticity of the thin films is based on inversion of frequency shifts of resonances of the substrate caused by the film deposition (projects 88,94). This technique was successfully used for elasticity determination of carbon-based films, and for detection of phase transformations in the shape memory (NiTi) films (projects 88,94,96). Further modifications enabled the RUS measurements in broad temperature range (from liquid nitrogen temperatures up to 1000K) and in dependence on the external (magnetic) field, and application of this method for characterization of a broad variety of advanced materials, ranging from single crystals to complex architectured composites. The laser-based resonant ultrasound spectroscopy has been successfully established in a wide field of material research, and enabled to open long-term national and international collaborations.
- The techniques based on surface acoustic waves (SAW) are less demanding for the sample preparations than the RUS method and enable also the determination of elastic properties of individual constituents in heterogeneous substances, such as polycrystals, multiphase and composite ceramics, intermetallics (martensitic laminates, multiphase structures), etc. The development of the SAW techniques at LUM (projects 88,91,94,96) was motivated by several significant advantages of this approach: i) only the surface of the material is affected; ii) shorter acoustic wavelengths (<10um) and higher frequency range (1GHz) are reached; iii) spatial localization of the measured area (10-50um) is enabled; iv) angular scanning over one measured surface (a generally oriented cut of an anisotropic material) enables to obtain anisotropic elastic moduli; v) the measurements can be performed under external pre-stress (which is utilizable for acousto-elastic measurements as well as for characterization of stress/stabilized phases of advanced materials) The developed instrumentations of the SAW techniques are again based on laser-ultrasonic approach: the laser radiation is used for the photothermal generation of elastic waves (either a cylindrically-focused excitation pulse as a broadband source, or a spatially periodic interference pattern as a narrowband source) and their detection is

also done optically, using either beam deflection and diffraction probes, or homodyne or heterodyne interferometric probes.

The main scientific outputs of the LUM team during the given period fall in to three categories: i) development of the ultrasonic methods themselves (Section 1 in the following list); ii) the use of these ultrasonic methods for characterization of advanced materials (Sections 2-6) ; iii) the mathematical modeling of the constitutive behavior of the studied materials (Section 7). The following list summarizes the most significant achievements by the LUM team, each supported by publications in widely accepted international journals.

1. Development of contact-less ultrasonic techniques for experimental characterization of anisotropic materials.

The possible applications of laser-generated ultrasonic waves (laser-ultrasound) for characterization of anisotropic materials were explored. The ability the of contact-less resonant ultrasound spectroscopy to determine all 21 independent elastic coefficients of a generally anisotropic (triclinic) material was analyzed by benchmark measurements on silicon single crystals and polycrystalline diffusion-bonded ceramics. In addition, a new experimental device for contact-less generation and detection of surface acoustic waves (SAWs) was developed together with a mathematical model of SAW propagation in general directions of anisotropic media based on the Ritz-Rayleigh method. The resulting approach was tested on measurements of elastic constants of an indium phosphide single crystal.

- P. Sedlák, H. Seiner, J. Zídek, M. Janovská, M. Landa, Determination of All 21 Independent Elastic Coefficients of Generally Anisotropic Solids by Resonant Ultrasound Spectroscopy: Benchmark Examples. Experimental Mechanics, 54 (2014) 1073-1085.
- P. Stoklasová, P. Sedlák, H. Seiner, M. Landa, Forward and inverse problems for surface acoustic waves in anisotropic media: A Ritz-Rayleigh method based approach. Ultrasonics 56 (2015) 381-389.

2. Ultrasonic Characterization of Acoustic Metamaterials.

Acoustic metamaterials are solids with artificially created periodic micro- or nano-structures that are responsible for strong wave-propagation anomalies in these materials. Within a long-term collaboration with the *Institute of Ceramics and Glass (ICV-CSIC) in Madrid (Spain)*, an analysis of elastic properties and the consequent acoustic wave propagation anomalies in such a material was carried out. The analyzed metamaterial was a periodic micro-scaffold fabricated of silicon carbide by the so-called Robocasting technique (3D printing), and was studied both experimentally (by means of resonant ultrasound spectroscopy) and by numerical modelling (finite elements method). This scaffold was shown to exhibit several unique metamaterial-like properties, not reported yet for any other material. The LUM team contributed to this research by resonant ultrasound spectroscopy measurements and finite elements modeling.

- A. Kruisová, H. Seiner, P. Sedlák, M. Landa, B. Román-Manso, P. Miranzo, M. Belmonte, Acoustic metamaterial behavior of three-dimensional periodic architectures assembled by robocasting. Applied Physics Letters, 105 (2014) 211904.

3. Mechanical properties of microstructures in ferromagnetic shape memory alloys

Smart alloys are materials able to modify their shape in response to external loadings; in the case of the ferromagnetic shape alloys in response to external magnetic fields. In cooperation with the *Institute of Physics CAS and Aalto University (Finland),* elastic and magneto-elastic properties of different phases and microstructures of the alloys Ni-Mn-Ga and Co-Ni-Al were examined. The LUM team contributed to this research by resonant ultrasound spectroscopy measurements as well as by theoretical models of the microstructure formation and pinning of the domain walls on the anti-phase boundaries.

The crystal lattice of the ferromagnetic shape memory alloy Ni_2MnGa is able to soften due to magnetostriction (so-called delta-E effect). This phenomenon was thoroughly studied by RUS. The main aim of this research was to show which part of the softening of this alloy is given by the magneto-elastic effects and which part is the structural softening due to the vicinity of the transition temperature. On this purpose, the measurements of the combined effect of temperature and external magnetic field on the elasticity of this material were done. The results have proved that the magneto-elastic effects are dominant, whereas the structural softening of the lattice is relatively weak and comparable to the softening of non-magnetic shape memory alloys.

- H. Seiner, O.Heczko, P. Sedlák, L. Bodnárová, M. Novotný, J. Kopeček, M. Landa, Combined effect of structural softening and magneto-elastic coupling on elastic coefficients of Ni-Mn-Ga austenite, Journal of Alloys and Compounds 577(2013), s131-s135.
- O. Heczko, H. Seiner, P. Sedlák, J. Kopeček, M. Landa, Anomalous lattice softening of Ni2MnGa austenite due to magneto-elastic coupling. Journal of Applied Physics 111(2012), 07A929

The effect of the microstructure on the mechanical, acoustic and thermomechanical properties of single- and multi-phase single crystals were studied for alloys Ni-Mn-Ga and Co-Ni-Al. Several important findings explaining the formation of microstructures and their interfaces at the macro level were achieved. Especially the role of antiphase interfaces and their influence on the magnetic domain structure in the alloy Ni-Mn-Ga, and influence of the Gamma particles on precursors of the phase transformation in the Co-Ni-Al alloy.

- H. Seiner, J. Kopeček, P. Sedlák, L. Bodnárová, M. Landa, P. Sedmák, O. Heczko. Microstructure, martensitic transformation and anomalies in c'-softening in Co–Ni–Al ferromagnetic shape memory alloys. Acta Materialia 61 (2013) 5869–5876.
- H. Seiner, P. Sedlák, L. Bodnárová, J. Drahokoupil, V. Kopecký, J. Kopeček, M. Landa, O. Heczko, The effect of antiphase boundaries on the elastic properties of Ni-Mn-Ga austenite and premartensite. Journal of Physics: Condensed Matter 25 (2013) 426402(1-10).
- O. Heczko, H. Seiner, P. Sedlák, J. Kopeček, V. Kopecký, M. Landa, Resonant ultrasound spectroscopy – a tool to probe magneto-elastic properties of ferromagnetic shape memory
alloys. European Physical Journal B 86 (2013) 62(1-5).

- O. Heczko, J. Kopeček, L. Straka, H. Seiner, Differently mobile twin boundaries and magnetic shape memory effect in 10M martensite of Ni–Mn–Ga. Materials Research Bulletin 48 (2013) 5105–5109.

4. Mechanical properties of advanced materials fabricated by plasma-based technologies

4.1. Characterization of in-situ functionally graded ceramics

The LUM team has developed a generalization of the resonant ultrasound spectrosocopy method, enabling also to measure samples with linear gradient of material properties, so-called functionally graded materials. We have employed the fact that the gradient induces an asymmetrization of the modal shaped of the eigenvibrations of the sample, and determined the gradients of shear modulus of the in-situ spark-plasma sintered ceramics.

- H. Seiner, P. Sedlák, L. Bodnárová, A. Kruisová, M. Landa, A. De Pablos, M. Belmonte, Sensitivity of the resonant ultrasound spectroscopy to weak gradients of elastic properties. Journal of the Acoustical Society of America,131 (2012), p. 3775–3785.

4.2 Anisotropic mechanical properties and micromechanics of materials with elliptically degenerated elasticity

The RUS method was applied to investigate the mechanical properties (elasticity, internal friction) of materials in which the anisotropy is induced by spatially oriented field inhomogeneities or defects. Specifically, the analyzed materials were ceramic composites with graphene nanoparticles (in collaboration with *the Institute of Ceramics and glass CSIC, Madrid)* and plasma coatings of steel (in collaboration with *the Institute of Plasma Physics CAS*). For both investigated materials, the theoretical assumption was confirmed that the anisotropy of such materials has a so-called elliptical degeneracy. This observation enabled the discussion of micromechanical processes taking place in these materials under mechanical stress.

- H. Seiner, P. Sedlák, M. Koller, M. Landa, C. Ramirez, M.I. Osendi, M. Belmonte, Anisotropic elastic moduli and internal friction of graphene nanoplatelets/silicon nitride composites. Composites Science and Technology 75 (2013) 93–97.
- P. Sedmák, H. Seiner, P. Sedlák, M. Landa, R. Mušálek, J. Matějíček, Application of resonant ultrasound spectroscopy to determine elastic constants of plasma-sprayed coatings with high internal friction. Surface & Coatings Technology 232 (2013) 747–757.

5. Ultrasonic analysis of thin functional layers and substrates for their growth

5.1 Characterization of Thin NiTi Films

Within a bilateral collaboration with the *Israeli Institute of Technology (Technion, Haifa)*, a research on thermomechanical properties of few micrometers thick sputtered NiTi layers was carried out. These layers are developed for applications in Micro- Electro- Mechanical systems (*MEMS*). By means of contactless ultrasonic methods, the temperature evolutions of elastic moduli of these layers were determined at LUM, and from these evolutions the critical temperatures for structural transition in the studied alloys were detected.

- M. Kabla, H. Seiner, M. Musilova, M. Landa, D. Shilo, The relationships between sputter deposition conditions, grain size, and phase transformation temperatures in NiTi thin films. Acta Materialia 70 (2014) 79-91.

5.2 Mechanical properties of DLC, NCD films

Thin coatings are increasingly broader branch in material science, electronics and biomedical applications. Standard methods for the investigation of their mechanical properties have limitations and shortcomings. A new ultrasonic method was proposed by the LUM team, based on changes in the resonant frequency of the specimen due to the deposition layer onto the substrate. Possibilities of a modified RUS method were tested on 100 nm (DLC) and 1um (NCD) layer deposited on silicon substrates (the samples prepared in the *Institute of Physics CAS*). The method is particularly suitable for investigation of in-plane elastic properties of the layer, it will be possible to implement in-situ in the deposition equipment and monitor the deposition process and changes the resonant frequency to estimate the level of residual stress.

- M. Růžek, H. Seiner, P. Sedlák, A. Kruisová and M. Landa, Linearized Forward and Inverse Problem of the Resonant Ultrasound Spectroscopy for the Evaluation of Thin Surface Layers, J. Acoust. Soc. Am. 128 (2010), 3426–3437
- T. Kocourek, M. Růžek, M. Landa, M. Jelínek, J. Mikšovský, J. Kopeček, Evaluation of Elastic Properties of DLC Layers using Resonant Ultrasound Spectroscopy and AFM nanoindentation, Surface and Coating Technology, Surface & Coatings Technology 205 (2011) S67–S70

5.3 Anisotropic elasticity of $DyScO_3$ substrates

Elastic constants of $DyScO_3$ single crystal were determined by ultrasonic measurements. Although these crystals are broadly used as substrate materials for epitaxial growth of thin layers, the accurate elastic constants for them were not available until the publication of this paper. The paper includes also a comparison of the experimental results with ab-initio calculations, showing that the calculations still cannot capture fully the elasticity of such complex oxide structures.

The reported work was done in collaboration of the LUM team with *the Institute of Physics CAS*. The IoP team provided the $DyScO_3$ samples and performed the ab-initio calculations. The LUM team contributed by the ultrasonic measurements (a dedicated modification of the RUS technique was developed on this purpose) and by a theoretical discussion of the results, especially of the relation between the atomic weight of the rare-earth element in RE-scandates and the elastic constants.

- M.Janovská, P.Sedlák, H.Seiner, M.Landa, P.Marton, P.Ondrejkovič, J.Hlinka, Anisotropic elasticity of $DyScO_3$ substrates. Journal of Physics: Condensed Matter. 24 (2012), art. no. 385404, p.1-8.

6. Elasticity of polycrystalline solids prepared by severe plastic deformation technologies

- Technologies using repeated plastic deformation such as ECAP (Equal-Channel Angular Pressing) enable the metallic polycrystalline materials to achieve very fine grain structure (up to the order of nm). These fine-grained materials exhibit unique mechanical properties such as enhanced strength, hardness, corrosion resistance and ductility. Their structure is not isotropic, it can be affected by texture (preferred orientation of grains and grain boundaries) as well as by grain shape and possibly subgrains. The structural anisotropy is reflected by the weak anisotropy of the elastic properties, that can be studied by ultrasonic methods. The RUS method was applied by the LUM team (in collaboration with *the Faculty of Mathematics and Physics, Charles University, Prague)* to analyze the elastic anisotropy evolution of poly- crystalline copper with multiple ECAP passes.
- H. Seiner, L. Bodnárová, P. Sedlák, M. Janeček, O. Srba, R. Král, M. Landa, Application of ultrasonic methods to determine elastic anisotropy of polycrystalline copper processed by equal-channel angular pressing, Acta Materialia 58 (2010) 235–247

7. Multiscale mathematical modelling of advanced materials

Supported by projects 82-84,86-88,90,93-95 and the project supporting the Czech_Germany scientific collaboration within the agreement between the Czech Academy of Sciences and DAAD Germany, (Bilateral project DAAD/14/11 between the *RWTH Aachen University* and the Institute of Thermomechanics CAS : Mathematical modelling of ferromagnetic shape memory alloys., H.Seiner, the principal investigator for CR, 2014-2015, the project is not included in the complete list of the form 3-1).

<u>7.1 Multi-scale models of structural transitions in ferroelastic and ferromagnetic materials</u>

Modeling of shape-memory alloys represents a multiscale problem due to the occurrence of a martensite/austenite phase transformation and a microstructure in the deformation gradient typical for a martensitic phase. Inspired by relaxation in a static situation, a limit passage between two modeling scales, called micro- and mesoscales, is performed for the corresponding evolution variants while considering activated phase transformation and even thermodynamically consistent thermal coupling. The mesoscopic model captures possible fine spatial oscillations of the deformation gradient by means of gradient Young measures. In particular, the mesoscopic model is justified as a limit from the microscopic scale and existence of its solutions is proved.

- B. Benešová, T. Roubíček, Micro-to-meso scale limit for shape-memory-alloy models with thermal coupling, Multiscale Modeling and Simulation 10 (2012), 1059-1089.

A similar approach of incorporation of the thermal coupling phenomena was also applied for the ferromagnetics, in particular for the para-ferro transition in micromagnetics.

- B. Benešová, M.Kružík, T.Roubíček, Thermodynamically-consistent mesoscopic model of the ferro/paramagnetic transition. Zeit. angew. Math. Phys., February 2013, Volume 64, Issue 1, pp 1-28**.**

The contribution of the LUM team to this topic was mainly in the convexity and consistency analysis of the proposed models and their numerical implementations.

7.2 Models of micromechanisms of formation and motion of martensitic microstructures and their experimental verifications

A novel model of the mobility of interfacial microstructures based on rate-dependent dissipation has been introduced and demonstrated on Cu-Al-Ni single crystal. Based on this understanding, further theoretical research on the mechanical stabilization effects and nucleation phenomena in single crystals of shape memory alloys was carried out. This work was based on the long-term collaboration between LUM IT CAS and *the Mathematical Institute of the Oxford University*, to which the LUM team contributes by experimental observations and physical concepts of the models.

- O. Glatz, H. Seiner, and M. Landa, Rate-Dependent Model of Mobility of Interfacial Microstructures in Shape Memory Alloys. Proceedings of the Fifth International Conference on Multiscale Materials Modelling MMM2010, P. Gumbsch and E. van der Giessen, Ed., October 48, 2010 (Freiburg), Fraunhofer Verlag, 2010, p. 58-61.
- J.M. Ball, K. Koumatos, H. Seiner, Nucleation of austenite in mechanically stabilized martensite by localized heating (2013) Journal of Alloys and Compounds, 577 (SUPPL. 1), pp. S37-S42.
- J.M. Ball, K. Koumatos, H. Seiner, An analysis of non-classical austenite-martensite interfaces in CuAlNi.. Proceedings of the International Conference on Martensitic Transformations, ICOMAT-08, pp. 383-390.

Calculations of elastic strains in weakly incompatible microstructures of the Cu-Al-Ni alloy were done, in particular the strain fields and the micromorphology of the twinned-to-detwinned interfaces appearing between the single variant of martensite and a 1^{st} order laminate of this alloy.

- H. Seiner, O. Glatz, M. Landa. A finite element analysis of the morphology of the twinned-to-detwinned interface observed in microstructure of the Cu–Al–Ni shape memory alloy. International Journal of Solids and Structures 48 (2011) 2005–201

Ferromagnetic shape memory alloys based on the Ni-Mn-Ga system are currently intensively studied. The main feature of these materials is their ability to form oriented microstructures that can be easily controlled by external magnetic or mechanic loads. A continuous research was carried out in the field of mathematical modeling of martensitic microstructures and the application of the outputs of these models to interpret experimental observations. Within a frame of broad international collaboration (*Aalto University of Technology (Finland), Adaptamat Ltd. (Helsinki, Finland), IFW Dresden (Germany)*) and in collaboration with the *Institute of Physics CAS*, a detailed analysis of microstructures of 10M-modulated martensite in Ni2MnGa shape memory alloy was conducted. The results have shown that the different mobility of twins in this alloy is given by the difference between the twinning systems of these twins. Theoretical models of such microstructures and their responses to external loads were developed. These models were then verified by a broad variety of experimental results.

- L. Straka, O. Heczko, H. Seiner, N. Lanska, J. Drahokoupil, A. Soroka, S. Fahler, H. Hanninen, A. Sozinov, Highly mobile twinned interface in 10 M modulated Ni–Mn–Ga martensite: Analysis beyond the tetragonal approximation of lattice. Acta Materialia 59 (2011) 7450–7463
- H. Seiner, V. Kopecký, M. Landa, O. Heczko, Elasticity and magnetism of Ni_2MnGa premartensitic tweed. Physica Statu Solidi B 251 (2014) 2097-2103.
- H. Seiner, L. Straka, O. Heczko, A microstructural model of motion of macro-twin interfaces in Ni-Mn-Ga 10M martensite. Journal of the Mechanics and Physics of Solids, 64 (2014) 198-211
- O. Heczko, L. Straka, H. Seiner, Different microstructures of mobile twin boundaries in 10 M modulated Ni–Mn–Ga martensite. Acta Materialia 61 (2013) 622–631.

<u>7.3 Experimentally justified development of constitutive models of polycrystalline shape memory alloys</u>

Phenomenological modeling of shape memory alloys was dedicated mainly to development of a 3D model. The development of the 3D model was based on a simple notion of the relation between the martensitic phase transformation and internal evolution of martensite, which was deduced from previous experiments. The model captures basic phenomena in SMA - superelasticity, martensite deformation, one-way shape memory effect, martensite stabilization by deformation and evolution of transformation hysteresis with temperature. The model was implemented as a UMAT in ABAQUS FEM code. The model was realized in collaboration with *LEMTA – ESSTIN, Université Henri Poincaré v Nancy (France)*. The model was applied to simulation of SMA wire structures

- Vokoun, D., Sedlák, P., Frost, M., Pilch, J., Majtás, D., Šittner, P., Velcro-like fasteners based on NiTi micro-hook arrays, Smart Materials and Structures, 20 (2011), 085027

A new constitutive model for NiTi-based SMAs was formulated and, based on it, a numerical model suitable for general thermomechanical loading was developed. A newly introduced dissipation function covers energy dissipation due to both phase transformation and reorientation processes in the martensite phase. The model is particularly suitable for NiTi-based alloys exhibiting intermediate R-phase transformation and/or material anisotropy due to texture. Numerical implementation was successfully tested on a set of benchmark experiments.

- P. Sedlák, M. Frost, B. Benešová, T. Ben Zineb, P. Šittner, Thermomechanical model for NiTi-based shape memory alloys including R-phase and material anisotropy under multi-axial loadings. International Journal of Plasticity, 39, 2012,132 -151.
- M. Frost, P. Sedlák, A. Kruisová , and M. Landa, Simulations of Self-Expanding Braided Stent Using Macroscopic Model of NiTi Shape Memory Alloys Covering R-Phase, Journal of Materials Engineering and Performance 23(2014) 2584-2590

- P. Sedlák, M. Frost, A. Kruisová, K. Hiřmanová, L. Heller, P. Šittner. Simulations of Mechanical Response of Superelastic NiTi Helical Spring and its Relation to Fatigue Resistance. J. Mater. Eng. Performance, 23(2014), pp. 2591-2598.

Laboratory of experimental stress analysis (EAN)

EAN deals with transient phenomena associated with stress wave propagation in solids. In the studied solids, stress waves are typically generated by various types both of falling strikers and by projectiles launched by small air guns. Dynamical responses are detected by miniature accelerometers, strain gauges or by laser vibrometers and the double pulse holointerferometry. This approach is applied to analyze dynamic properties of soft biological materials, foodstuffs, food products. Several miniature Split Hopkinson pressure bar testers have been developed for these purposes.

Nondestructive characterization of defects in thin wall shells using acoustical wave propagation (supported by the project 85)

The study was concerned with experimental and theoretical interpretation of non-stationary wave phenomena occurring in impacted thin-walled shells. The analysis of these phenomena can detect and localize structural imperfections such as unwanted masses on the shell surfaces or simple deliberate defects. The analytical solution is not known, so that it is necessary to combine experimental and numerical approaches and compare respective results. The wave phenomena in the vicinity of the defects were analyzed by means of the hybrid diagnostic method covered contact or contactless laser-based detection techniques.

- J. Trnka, P. Stoklasová, C.S.P. Norris: Detection of Suspicious Mass on Structures by Acoustical Waves. Experimental Techniques. 36 (2012), 14-21.
- J. Buchar, R. Řídký, M. Drdlová, J. Trnka: Numerical and Experimental Analysis of Multilayer Mine Protection. Applied Mechanics and Materials 732 (2015), 49-54

Dynamical behaviour and rheological properties of foodstuffs and selected agriculture products

(supported by the collaborative contracts)

In the collaboration with *Mendel University in Brno (Mendelu)*, there were studied mechanical responses of the selected agricultural products (fruits, cheeses and eggs) on impact loadings.

The response was evaluated by history of the displacement and/or velocity of the product surface.

The spectral analysis of the dynamical response of various types of cheeses revealed that the ageing process is related to parameters of the dominant frequency. The dynamical approach seems to be a promising tool for quality control of these food products.

The influence of the products firmness as well as the effect of the cracks of the eggshell was studied. Evaluation of the material properties at high rates of strain which correspond to the impact conditions.

The finite element model of the egg was developed. The numerical simulation was performed using LS DYNA 3D. The computations exhibit very good prediction of the experimental data.

- L. Severa, J. Trnka, J. Buchar, P. Stoklasová, Š. Nedomová: Changes in Rheological Properties of Hard Cheese during its Ageing. 1. New York: Nova Science Publisher Inc, (2011), 77. (Food Science and Technology). ISBN 978-1-61209-722-0. 1.
- Š. Nedomová, L. Severa, J. Buchar, J. Trnka, P. Stoklasová,: Study of Hen's Eggs Behavior Under Impact Loading. 1. New York: Nova Science Publisher Inc, (2011), 86. (Animal Science, Issues and Professions, Mechanical Engineering Theory and Applications). ISBN 978-1-61761-587-0.1.
- J. Trnka, J.Buchar, L. Severa, Š. Nedomová, P. Stoklasová: Effect of Loading Rate on Hen's Eggshell Mechanics, Journal of Food Research; 1 (2012), 1927-0895
- Š. Nedomová, J. Trnka, J. Buchar, P. Stoklasová: Response of the Ostrich eggshell to non destructive impact. Advances in Applied Acoustics. 2 (2013), 71-76.
- J. Trnka, P. Stoklasová, J. Strnková, Š. Nedomová, J. Buchar: Vibration properties of the ostrich eggshell at impact. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis. 61 (2013), 1873-1880.
- J. Strnková, Š. Nedomová, J. Trnka, J.Buchar, J. Simeonovová: Behavior of Cracked Eggs at Non– Destuctive Impact. J. Microbiol Biotech Food Sci., (2014), 43-50
- J. Trnka, P. Dvořáková: Transient Stress Waves in Study of Coconut Physical Properties.Experimental Techniques. 34 (2010), 19-25.
- Š. Nedomová, J. Trnka, J. Buchar: Tensile strength of dark chocolate. Acta Technologica Agriculturae. 3 (2013), 69-71.
- J. Buchar, L. Severa, J. Trnka, Š. Nedomová, A. Bubeníčková, P. Stoklasová, J. Simeonovová, M. Jůzl: Novel Techniques in the Evaluation of Potatoes Mechanical Properties. Part of monography Applications of Physical Research in Engineering. Slovak University of Agriculture, Nitra, (2012) - (Božiková, M.; Hlaváčová, Z.; Hlaváč, P.), 74-90 ISBN 978-80-552-0930-2.

Research Report of the team in the period 2010–2014

Institute	Institute of Thermomechanics of the CAS, v. v. i.

Scientific team	Department D 6 - Electrical Engineering and Electrophysics

Introduction

The Department of Electrical Engineering and Electrophysics focuses on basic and applied research in the following areas:

- Dynamics of Electrical Machines and Drives
- Power Electronics
- Coupled Problems in Electrical Engineering
- Electrophysics

The current challenges of power engineering, such as the power quality and the stability of the power grid with a large ratio of renewable energy sources, impose new demands on the research in electrical engineering. At present, the research is influenced to a great extent also by the current progress in the field of electromobility. There are also a number of emerging industrial applications, particularly in induction heating, plasma spraying, plasma cutting or plasma chemistry, where the achieved results can be effectively utilized.

Organizational Structure

The head of the Department is M. Chomat, PhD. The Department is organizationally structured into four laboratories, which are briefly described below.

Laboratory of Dynamics of Electrical Machines and Drives

Head: L. Schreier, PhD

The Laboratory is engaged in the analysis and modelling of electric drives and rotating machines along with experimental verification of the achieved results. The most important methods for the conversion of mechanical energy into electrical energy and vice versa are analyzed. Considerable attention has been given to systems with doubly fed machines, which can operate at variable speed and thus seem to be promising generators for wind and hydro power plants. Another goal is to propose effective measures for keeping the drive in operation even if some of its components fail. A related area of research is finding the ways for the compensation of unbalanced three-phase power supplies of converters that can significantly deteriorate the operating characteristics of electric drives in practice. In recent years, increasing attention has been paid to the field of multiphase machines.

Laboratory of Power Electronics

Head: R. Semerad

Research is focused on current problems connected with the circuit structures of power electronic converters and algorithms for their control and diagnostics. The mutual effects of converters with the machines that are fed from them and the supply networks they are connected to are analyzed. Advanced control algorithms of AC drives and multilevel frequency converters are developed and tested experimentally. The ways for avoiding the unfavorable high-frequency phenomena (electromagnetic interference) produced by solid-state converters are studied. Digital models of the drive components, which are also valid at high frequencies, are proposed and verified. In the field of electromagnetic compatibility (EMC) in electric power engineering, control algorithms for active power filters are developed in order to compensate for higher harmonics, unbalanced loads, power factor and flicker, as well as to control the energy flows in industrial networks.

Laboratory of Coupled Problems in Electrical Engineering

Head: prof. I. Dolezel, PhD

Advanced versions of numerical methods are developed for the solution to physical fields. These are primarily higher-order finite element methods with automatic adaptivity, supplemented with technologies of hanging nodes and independent discretization meshes for the individual physical fields as well as some integral methods. These methods are then applied to the solution to selected coupled problems in the area of electrical power engineering, EMC and in several other technical problems. It is particularly the modelling of physical processes during the thermal processing of solid and liquid metals controlled by electromagnetic field (induction heating, induction hardening, electromagnetic hot pressing, levitation melting, mixing, pumping and dosing of liquid metals and other technological procedures) that is in the forefront of our interest.

Laboratory of Electrophysics

Head: J. Sonsky, PhD

Research is carried out into the dynamic phenomena and coherent structures in electrical arcs and in thermal plasma plumes including the interaction of these structures with injected particulate matter. During most of the experiments, the thermal plasma is generated by an electrical arc in a plasma torch. Advanced optical methods, primarily those making use of high-speed CCD cameras and multichannel systems working with optical fibers and photodiodes, are employed to monitor the plasma jet at the plasma torch outlet. Scanning from multiple directions makes the spatial reconstruction of the dynamic processes in the plasma jet possible and enables achieving a high temporal resolution. Correlation analysis methods, Fast Fourier Transform, wavelet analyses and correlation dimension calculations are used to process the experimental data obtained.

Equipment

The Department has got several laboratories for measurements on electric machines and drives up to the output power of 120 kW. The laboratories are equipped with several dynamometers, with a number of high-quality measuring devices and modular control systems as well as with equipment for EMC measurements. A wide range of rotating electric machinery is available for experiments, too. Development tools for microcontrollers are at our disposal. A modular dSPACE system enables rapid implementation of control algorithms for electric drives. Adequate computer facilities and simulation programs (MATLAB/Simulink with toolboxes, COMSOL Multiphysics, ANSYS, etc.) are available. Some of the specialized devices and control programs have been developed directly at the Department.

The measurements of thermal plasma and electric arcs up to 500 A can be carried out in the laboratories of the Department. The laboratories are equipped with high-speed fast-shutter cameras and a unique multi-channel fiber-optic system with a sampling frequency up to 2 MHz, which was developed at the Department. Optical diagnostics is also capable of performing spectroscopic measurements and Schlieren imaging. Plasma torches of different constructions can be used for experiments, including a water-cooled rotating anode with a current capability up to 400 A for transferred arc types (cutting plasma torches).

The above mentioned facilities represent excellent prerequisites for the experimental verification of theoretical results achieved by the research team.

Domestic and International Co-operation

The members of the research team have extensive contacts with a number of renowned research institutions abroad. There is effective collaboration with universities and research institutions involved in similar research areas, e.g. with the Institute for Drive Systems and Power Electronics, Leibniz University Hannover, Germany; the University of Wisconsin-Madison, USA; the Faculty of Electrical Engineering, Czech Technical University in Prague; the Faculty of Electrical Engineering, the University of West Bohemia in Pilsen; or the Faculty of Electrical Engineering and Communication, Brno University of Technology.

The Department has been co-organizing international symposia with the above mentioned Institute for Drive Systems and Power Electronics at Hannover since 1988. Members of the research team participated in several research exchange visits at foreign universities and the Department hosted several visiting researchers from other research institutions and universities. The Department is a Competence Center of the European Center for Power Electronics. Long-term co-operation with several industrial companies in the Czech Republic is established, with e.g. CKD Elektrotechnika, a.s., ATAS Elektromotory a.s., EMP s.r.o., or Thermacut, s.r.o.

Research Activities

The research at the Department is mostly done in the framework of research grant projects and in co-operation with industrial partners. During the evaluation period between 2010 and 2014, the researchers of the Department participated in 7 research grant projects funded by the Czech Science Foundation (ID numbers 99 – 105 in form 3.1), in 3 research grant projects funded by the Grant Agency of the Czech Academy of Sciences (ID numbers 97, 98, and 108 in form 3.1), and in 2 research grant projects funded by the Grant Agency of the Ministry of Industry and Trade of the Czech Republic (ID numbers 106 and 107 in form 3.1). The overall financial support from these agencies reached 694 thousand EUR. The research for practice was done in the framework of 4 contractual research projects (ID numbers 90 - 93 in form 3.2) and 6 collaborative research projects (ID numbers 106 - 111 in form 3.2). The overall financial income from these applied research projects was 102 thousand EUR.

The researchers published 66 papers in reviewed scientific journals, including 47 in journals with the Impact Factor, 2 book chapters, and 9 internal research reports during the evaluation period. The researchers presented over 100 contributions at international scientific conferences. A member of the Department acted as an editor of an open-access book. The results of the applied research have been protected by 8 Functional Models or Utility Models issued by the Patent Office of the Czech Republic. The people from the Department were significantly involved in editorial activities associated with publishing the scientific journal Acta Technica CSAV by the Institute. They also participated in research projects carried out at the other departments of the Institute, where they offer their knowledge and competencies in the field of electrical engineering and electronics.

The major research achievements obtained in the research areas covered by the Department are briefly described below.

Research Area: Dynamics of Electrical Machines and Drives

Result: Reliability and Failure Tolerance of AC Variable-Speed Drives

Researchers Involved

L. Schreier, M. Chomat, J. Bendl, M. Skalka

Description

The reliability of variable-speed AC drives is an issue of high importance for industrial applications. The concept of a fault-tolerant drive system enables satisfactory operation even after the occurrence of a failure. A dynamic model of a three-phase induction motor with a pulse-width modulation (PWM) inverter was created in MATLAB/Simulink. The model was used to study the behavior of the induction motor during various dynamic processes. An improved model of an AC/DC converter with PWM in the form of a set of differential equations, formulated by using the Lagrange method, was developed.

Analysis of processes in multi-phase induction machines has been carried out, aimed particularly at five-phase and six-phase machines. The relation between the symmetrical components of the instantaneous values of phase currents and the groups of spatial harmonics of the current layer was explained and the influence of these harmonics on the currents and torque of the machine was studied and assessed. The results of the analysis were used to examine properties of such machines in various steady and transient states.

The properties of these machines were compared with those of the commonly used three-phase machines with respect to their fault tolerance. It has been shown that with increasing number of phase windings the additional losses decrease, the magnitude of parasitic pulsating torques increases, and the time period during which the machine can work in emergency operation becomes longer, which results in improved fault tolerance.

Participation of Research Team

The main theoretical and experimental results given above were achieved at the Department. The Czech University of Agriculture in Prague participated in the theoretical investigation of devices in the time and frequency domains using the mixed p-z approach.

Associated Grant and Collaborative Projects

ID number: 99 (Form 3.1)

Main Outcomes

ASEP ID: <u>0351252</u>, <u>0351142</u>, <u>0351144</u>

<u>Result: Minimizing DC-Link Voltage Variations in Voltage Source Inverters</u>

Researchers Involved

M. Chomat, L. Schreier, J. Bendl

Description

The research was focused on electric drives fed by unbalanced supply voltages. The unbalance gives rise to voltage pulsations in the DC bus of voltage-source inverters, which may negatively affect the properties of the drive and eventually lead to a serious failure or even damage of the driven device. Based on the analytically derived equations, control methods were proposed that can minimize the negative effects of the voltage-supply unbalance on the DC-link voltage. The effects of these methods on narrowing the control range of the drive were examined. It has been shown that proper control can significantly diminish the undesired impacts of the current unbalance or improve the power factor at the input. Thorough investigation of the influence of voltage pulsations in the DC bus on connected electric machines and on the power grid was carried out. Operation of the system in steady states as well as in various transient states was examined. The proposed control methods and other theoretical results achieved in the framework of the project were experimentally verified on the developed drive system.

Participation of Research Team

The result was achieved entirely by the members of the research team of the Department.

Associated research grants, collaborative/contractual research projects

ID number: 100 (Form 3.1)

Main Outcomes

ASEP ID: <u>0352053</u>, <u>0352568</u>, <u>0352055</u>, <u>0370688</u>, <u>0370688</u>, <u>0364181</u>, <u>0361024</u>

<u>Result: Control of Multi-Phase Electric Machines</u>

Researchers Involved

M. Chomat, L. Schreier, J. Bendl, T. Vecerka

Description

The research was aimed at analyzing multi-phase electric machines and developing advanced control methods for drives with such machines. The multi-phase machines have several advantages over the three-phase machines, which makes them suitable for certain applications, e.g. for drives in means of transportation or for special drives in industry. Their advantages include improved tolerance against failures occurring in the machine or in the feeding converter, smoother waveforms of torque and a possibility of using a lower supply voltage. There are still a number of problems associated with the machine properties and behavior, which have not been satisfactorily explained yet. This is the reason that prevents their wider utilization in practice. Our attention is paid particularly to multi-phase induction and permanent magnet synchronous machines. A new methodology for solving problems of these machines in the operating or fault states was proposed and advanced control methods for electric variable-speed drives with such types of machines were developed.

Participation of Research Team

The result was achieved entirely by the members of the Department.

Associated Grant and Collaborative Projects

ID number: 101 (Form 3.1) - the solution of the project continues in 2015

Main Outcomes

ASEP ID: <u>0437384</u>, <u>0431808</u>, <u>0421565</u>, <u>0421596</u>

Research Area: Power Electronics

<u>Result: New Space Vector Modulation Strategies and Analytical Solution to Current Responses for Grid Connected Four-Switch Converter and Hybrid Power Filter</u>

Researchers Involved

V. Valouch, J. Skramlik, P. Simek, M. Bejvl

Description

A three-phase four-switch shunt hybrid power filter (HPF) with a new circuit topology aimed at compensating the reactive power and higher harmonics of the load was proposed and analyzed. The HPF has a reduced number of power switches, which improves the filter efficiency. A space-vector PWM scheme was adopted to reduce the switching state of converter power switches. Proper voltage vectors for drawing nearly sinusoidal line currents with a controllable power factor were generated at the AC terminal in the case of the proposed control scheme. An original closed-form solution to line currents, based on the mixed p-z approach, was presented. The analytical results were proved experimentally.

Properties of the new HPF were compared with those of two usual options of the HPF and of the classic passive filters. The results confirmed the advantage of the new HPF. The voltage and current responses and their harmonic spectra were also measured under different conditions in industrial plant Remarkplast, Ltd., Czech Republic, and compared with those obtained from the developed simulation model of the industrial network to verify the accuracy of this model. The topology and control strategy of the new HPF were implemented into the model of the industrial network in order to test its capability and prove the advantages over standard HPF topologies for filtering out unwanted harmonic currents.

The performance and effectiveness of an active power filter (APF) or HPF also depend on the point of their connection into the multibus industrial/distribution power system. The problem of multiple APF – multiple harmonic was formulated and applied to the control strategy of the node voltage detection.

Participation of Research Team

The research was done in co-operation with the Faculty of Electrical Engineering, Czech Technical University in Prague.

Associated Grant and Collaborative Projects

ID number: 97 (Form 3.1)

Main Outcomes

ASEP ID: 0432616, 0393345, 0380760, 0376132, 0347448, 0347976

Result: Modern Power Theories and Compensation Algorithms

Researchers Involved

V. Valouch, J. Skramlik, P. Simek, M. Bejvl

Description

The relevance of problems related to the presence of distorted waveforms in electrical systems has been pointed out in the first half of last century, when the two most important basic electric power theories were formulated. But at present, the grid voltage waveform may be influenced by large, dynamic and nonlinear loads much more than before. These loads produce unbalanced, non-periodic, and even stochastic currents. Increased penetration of distributed generation resources in the grid in the last two decades has led to interest in the development of new methodologies for the control of grid-connected inverters.

The principle and usage of the generalized non-active and instantaneous power theories for parallel compensation of periodic and non-periodic load current disturbances by active and hybrid power filters were analyzed in detail. Selected new power theories and compensation algorithms were tested in simulations as well as by measurement on the laboratory model. The injection of negative-sequence currents has been shown to be an effective tool for suppressing the oscillations in the converter DC-link voltage occurring due to oscillations of the power injected into the grid during unbalanced voltage sags. A variety of solutions to the calculation of the current references in such cases were proposed.

Participation of Research Team

The research was done in co-operation with the Faculty of Electrical Engineering, Czech Technical University in Prague, and with CKD Elektrotechnika, a.s.

Associated Grant and Collaborative Projects

ID number: 106 (Form 3.1)

Main Outcomes

ASEP ID: 0428547, 0436832, 0393236, 0396285, 0376231, 0383473, 0383503, 0349856

Result: Development of Medium-Voltage Flying-Capacitor Converter

Researchers Involved

P. Kokes, R. Semerad

Description

A four-level 8 MVA/10 kV converter based on IGCT switches and controlled by EmadynD controller was built and successfully tested in CKD Elektrotechnika, a.s. This frequency converter Invert (consisting of four-level active front end and four-level voltage-source inverter) was awarded the Golden Ampere Prize at the 24th International Trade Fair of Electrotechnics, Electronics, Automation, Communication, Lighting and Security Technologies held in Prague in 2011. Its successor is a seven-level flying-capacitor (FC) converter with a special design, referred to as the 4-7L converter, where three out of five flying capacitors in each phase leg have substantially reduced capacitances. This design provides some technical advantages, e.g. the omission of serial connection of IGBTs and improved economy. It was awarded the Golden Ampere Prize in 2015, too. Problems of multilevel vector modulation and voltage balancing of flying capacitors were solved. Conditions for the application of four-level modulation in the 4-7L converter were studied. Three methods of voltage balancing were proposed and verified by simulations. The 'simple' balancing method was implemented in the software and hardware of the EmadynF controller. To prove the quality of the balancing methods, of the PWM, and of the motor control algorithms, a low-voltage (LV) 5 kVA model of the 4-7L converter was built, which provided maximum similarity to the medium-voltage (MV) converter Invert 7L constructed in CKD Elektrotechnika, a.s.

Participation of Research Team

The theoretical part and experimental verification of the results were done at the Department. The co-operating CKD Elektrotechnika, a.s. specified the requirements, provided sensors, FPGA implementation and microcontrollers for creating the LV converter model, built an MV prototype for experiments, and carried out the tests.

Associated Grant and Collaborative Projects

ID number: 107 (Form 3.2)

Main Outcomes

ASEP ID: 0357300, 0421380, 0420900, 0421505, 0363422

Result: Development of Control Systems for Medium-Voltage Industrial Applications

Researchers Involved

P. Kokes, R. Semerad

Description

Several control systems for applications utilizing MV multilevel converters were developed. These are the control system of the induction motor, the control system of the synchronous motor, the control system of the PWM active front end rectifier, and the control system of the active parallel filter. The above systems were numerically simulated, implemented into an embedded controller and tested with LV converters in the Department and with the MV converter in CKD Elektrotechnika, a.s. The EtherCAT network was used to transfer the data between the PC and the controller. The Department also participated in the development of EtherCAT Slave system software.

We co-operated in the design and tests of EmadynF controller, which consists of an FCP unit with a dual-core CPU (C6000+ARM) and several DSU external units. The FCP and DSU units communicate via fast optical links. DSU functions were implemented mainly in Spartan3E FPGA, e.g. hardware part of PWM modulators, voltage balancing of flying capacitors, decoding sensor signals, fault detection and reaction, data logger, etc.

Participation of Research Team

The theoretical part, software implementation and experimental verification of the results were done by the Department. The co-operating CKD Elektrotechnika, a.s. specified the requirements, was responsible for Master software, provided the microcontrollers for experiments and cooperated in MV application tests. ASIX, Ltd., made a low-level/PCB design and manufactured the EmadynF controller and implemented its functions into FPGA.

Associated Grant and Collaborative Projects

ID number: 107 (Form 3.1) and 106, 108, 109, 110, 111 (Form 3.2)

Main Outcomes

ASEP ID: 0384069, 0438517, 0421385, 0421382, 0399933, 0421057

Research Area: Coupled Problems in Electrical Engineering

Result: Algorithms for Fully Adaptive Higher-Order Finite Element Method

Researchers Involved

I. Dolezel, P. Solin, P. Kus, L. Musalek, E. Skrivanova

Description

In the last five years, the team has developed advanced algorithms for the fully adaptive higher-order finite element method intended for numerical solutions to evolutionary multiphysics problems. The results were implemented in the library Hermes, which is a C++ library for rapid development of adaptive hp-FEM and hp-DG solvers. This library is used by the application Agros2d (www.agros2d.org) developed at the partner´s workplace in Pilsen that exhibits a number of quite unique and powerful algorithms such as:

- *h*, *p* and *hp* versions of adaptivity,

- top multimesh technologies (each physical field is solved on a different mesh that best fits its character),
- dynamic meshes for evolutionary problems,
- using of hanging nodes of any order,
- combination of various elements including curved elements,
- specific ways of numerical integration, etc.

The algorithms were used for the solution to numerous multiphysics problems, for example in electromagnetic processing solid and molten metals, proposal of specific electric devices (such as actuators), design of induction shrink fits and many others. The results of the above research were published in impacted journals (about 20 papers in the last five years) and presented at numerous international conferences.

Participation of Research Team

The above results were obtained in the framework of a common grant project with the Czech Technical University in Prague and with the University of West Bohemia in Pilsen. That is why the research team closely cooperated with the participating university teams. Just such close collaboration has allowed for the development of the application Agros, which makes it possible not only to solve complex multiphysics tasks but also to perform the shape optimization of particular devices, and sensitivity analysis of their parameters with respect to input data. At the same time, the researchers of the team could transfer their knowledge to both the participating universities in the form of courses, mainly for doctoral students.

Associated Grant and Collaborative Projects

ID number: 105 (Form 3.1) - the solution of the project continues in 2015

Main Outcomes

ASEP ID: 0439893, 0347689, 0439895, 0363238, 0437395, 0347677

Research Area: Electrophysics

Result: Temperature Measurements in Non-Stationary Thermal Plasma, Influence of Plasma Instabilities.

Researchers Involved

J. Hlina, J. Sonsky, J. Gruber

Description

Progress in technologies utilizing plasma torches is closely connected with the development of new approaches aiming at realistic description of the conditions in thermal plasmas. Our research has set up a new approach to the diagnostics of physical parameters, especially of temperature, in thermal plasma jets using tomographic methods with high temporal resolution. These methods offer new possibilities in optical diagnostics of asymmetric and non-stationary thermal plasmas. Temperature measurements present a special problem of the diagnostics of such plasmas and need careful consideration regarding the particular gas properties and the choice of a proper spectral range for measurements. An approach, based on measuring the optical emission of plasma in wide spectral intervals, has to be adopted to ensure a sufficiently strong signal for fast optical recording. The measurement system and evaluation methods were entirely developed at our laboratory. The solution involved construction of a unique optical system for multi-directional measurement of plasma radiation working with array detectors composed of optical fibers and photodiodes, and the development of evaluation methods based on MATLAB procedures. The method was first applied to argon plasma and then extended to air plasma, which is closer to technological applications. The research also dealt with instabilities affecting plasma temperature and with methods for their suppression. The investigations have brought new findings on short-time and spatial characteristics of temperature fields and instabilities involved.

Participation of Research Team

The principal experimental part of the research was carried out in the Department. The theoretical part, consisting in computations of the plasma radiation in various spectral intervals depending on the plasma composition, temperature and thickness, was carried out at the Laboratoire Plasma et Conversion d'Energie, a common laboratory of the CNRS, Institut National Polytechnique of Toulouse, and the University Paul Sabatier of Toulouse.

Associated Grant and Collaborative Projects

ID number: 108 (Form 3.1)

Main Outcomes

ASEP ID: 0337730, 0346974, 0384558, 0395514, 0437748

Result: New Methods for Time-Series Analysis, Application to Unstable Thermal Plasma

Researchers Involved

J. Gruber, J. Hlina, J. Sonsky

Description

Thermal plasma jets generated by DC plasma torches exhibit complex structure and dynamics. The plasma jet departs from the cylindrical symmetry due to mixing effects and due to unstable and asymmetrical arc attachment. The structure of a plasma jet can be examined experimentally by recording the plasma optical radiation with sufficient spatial and temporal resolutions.

Our research focused on the development of new methods for time-series analysis, which either combine the existing methods with tomographic reconstructions and extend results to 2D and 3D, or adjust the methods for invariant characteristics of deterministically chaotic dynamics and their modification for thermal plasma analysis. These methods are based on correlation dimension estimates. The measurement system and evaluation methods were fully developed in our laboratory.

The method was first applied to records of arc current and then extended to argon plasma radiation. The research also dealt with application of correlation analysis for estimating the velocity profile of plasma flow and its dependence on the input current. The investigations have brought new findings concerning the inner structure of thermal plasma jets and identified structures and their dynamics unrecognized by previous methods.

Participation of Research Team

The research was carried out at the Department. It involved constructing and fine-tuning a unique experimental system, carrying out the experiments, developing new methods for the analysis of the experimental data, and comparing various methods.

Main Outcomes

ASEP ID: 0366789, 0364164, 0363646, 0386101, 0363825, 0443419

Result: Contribution to Diagnostics and Development of Plasma Cutting Torches

Researchers Involved

J. Gruber, J. Sonsky, J. Hlina

Description

Plasma arc cutting is finding numerous applications in metal cutting. The structure of the arc during the cutting is very complex due to high temperatures, great temperature and pressure gradients, supersonic velocities and complicated interaction of the arc with the electrodes and the surrounding atmosphere. Important parts of the process influencing the dynamics and plasma parameters take place in areas that are hard to access, e.g. on the plasma-material boundaries, inside hollow electrodes or other structures without simple axisymmetry. The boundary and sheath regions of thermal plasmas, including processes in the cathode region, still remain a subject of controversy and present a challenge.

Our research focused on the examination of plasma radiation in the cutting plasma torch cathode area and in the electric arc during the whole cycle of the cutting torch operation (from inserting a new cathode to the cathode failure) in an effort to better understand the arc interaction with the cathode during this cycle. The process of ejection of molten material was observed by a high-speed camera, quantified, and the observed changes in the optical radiation of the arc were studied. A specially crafted nozzle was constructed.

We employed the wavelet analysis to evaluate the amount of ejected material during the cathode lifecycle, examined the influence of cycle duration on the rate of the loss of the cathode material, and measured the amount of burnout in the cathode tip. A description and understanding of these phenomena is important for verifications of models, for further improvement of consumables life-time, and for better control of cutting-arc parameters.

Participation of Research Team

The research was carried out at the Department. It involved modification of the commercial cutting plasma torch system and design of system for data acquisition. A water-cooled anode was used to suppress cutting and modification of the cutting torch nozzle, allowing for observation of its inner parts including the cathode tip. The analysis of the resulting records was done in MATLAB.

Main Outcomes

ASEP ID: 0395503, 0429753