UNIVERSITY OF PETROȘANI

RESEARCH ON THE FRETTING PHENOMENON. QUALITY AND TECHNOLOGY TRANSFER

HABILITATION THESIS

ABSTRACT

Field: Industrial Engineering

prof. dr. eng. Ștefan Sorinel GHIMIȘI

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RESEARCH ON THE FRETTING PHENOMENON. QUALITY AND TECHNOLOGY TRANSFER

The habilitation thesis entitled **"Research on the Fretting Phenomenon. Quality and Technology Transfer,"** developed in the field of **Industrial Engineering**, presents a synthesis of the scientific activity carried out after obtaining the PhD degree in engineering, highlighting the original contributions in the fields of contact mechanics, the durability of mechanical systems, and the integration of quality management into engineering processes and industrial applications.

The core of the research is the investigation of the **fretting phenomenon**, a complex degradation process occurring in mechanical contacts subjected to cyclic loading and relative micro-sliding. The importance of this phenomenon derives from its major impact on the reliability and safety of industrial equipment, being frequently encountered in the energy, extractive, aeronautical, and machine-building industries.

The original scientific contributions include the development of a rigorous analytical framework for determining the stress and strain fields in a **sphere-on-plane contact** subjected to combined normal and tangential loads, specific to the fretting phenomenon. The analysis was grounded in the use of the classical elastic half-space solutions (**Boussinesq–Cerutti**), extended through the application of Green's functions for variable pressure distributions and distributed tangential loading. This approach enabled the explicit determination of the principal stresses, equivalent stress, and pressure distribution both inside and outside the contact zone.

An element of originality lies in the **non-dimensionalization** of the obtained relationships through the introduction of characteristic parameters (the ratio between tangential and normal load, the coefficient of friction, the contact radius, and the reduced elastic modulus). This non-dimensional formulation made it possible to generalize the results for a wide range of loading conditions and materials, facilitating the direct comparison of different contact regimes and the identification of critical thresholds for the transition between elastic and plastic behavior.

The analysis of stress distribution highlighted the significant influence of the coefficient of friction on the position and maximum value of the principal stresses and the equivalent **Von Mises stress**. It was demonstrated that, as the coefficient of friction increases, the stress concentration zone shifts toward the edge of the contact, where maximum values of tangential stress and equivalent stress occur. This zone was identified as critical for the initiation of fretting fatigue cracks, in agreement with experimental observations regarding the occurrence of subsurface microcracks.

To assess the probability of damage initiation, modern strength criteria were applied, particularly the **Von Mises criterion** for plasticity analysis and fatigue criteria based on cyclic stress amplitude and the energy dissipated within the contact. The dependence of these criteria on geometric parameters (radius of curvature, size of the contact area) and mechanical parameters (elastic modulus, coefficient of friction, level of normal and tangential loading) was analyzed. The results revealed the existence of a critical range of parameters in which the transition from elastic to elastoplastic behavior occurs, associated with the progressive accumulation of damage.

An important contribution consists in the analysis of the **stress concentrators** generated at the contact edge and their role in initiating the fretting fatigue process. It was demonstrated that the non-uniform distribution of tangential stresses leads to the occurrence of steep stress gradients, favoring the nucleation of microcracks at shallow depths beneath the contact surface.

The theoretical modeling was extended through the development of an **elastoplastic model of fretting contact**, capable of describing the evolution of the stress state under cyclic loading conditions and integrating the effects of local plastic deformation. The model allows the description of pressure redistribution within the contact zone and the appearance of the **third body** formed by wear particles. By integrating plastic behavior into the contact analysis, a more realistic description was obtained of damage evolution and of the transition between wear-dominated and fatigue-dominated regimes.

The analytical results were correlated with numerical simulations carried out using the **finite element method (FEM)**, employing three-dimensional models of sphere-on-plane contact, as well as with experimental investigations performed on dedicated fretting test rigs. The correlation between theoretical, numerical, and experimental results enabled the validation of the developed models and the identification of the dominant damage mechanisms, contributing to the formulation of predictive criteria for assessing the service life of mechanical components subjected to fretting.

Through this integrated approach—**analytical, numerical, and experimental**—results were obtained that extend the classical framework of contact mechanics and provide both theoretical and practical tools for the analysis and prevention of fretting damage in industrial mechanical systems.

A second major research direction concerns the **increase in the durability and reliability of industrial mechanical systems** by developing integrated methods for the analysis, assessment, and optimization of the in-service behavior of components subjected to complex loading conditions. This research direction is based on correlating material mechanics, stress analysis, and damage criteria with advanced numerical methods and experimental validation.

In this context, methodologies were developed for assessing the degradation state based on stress-field analysis and the application of strength and fatigue criteria. The proposed approach involves determining the distribution of principal stresses and equivalent stress in critical component areas, identifying stress concentrators, and assessing the degree of proximity to plasticity or fatigue limits. Both static and cyclic loading regimes were analyzed, with particular emphasis on damage accumulation over time and crack initiation mechanisms.

For components subjected to cyclic loading, predictive models were developed for service life estimation, based on correlating stress amplitudes with the characteristic fatigue curves of materials. Deterministic and probabilistic approaches were integrated in order to estimate the remaining service life and evaluate the risk of failure. The developed models make it possible to quantify the influence of geometric parameters, loading conditions, and material properties on the overall reliability of the mechanical system.

An essential role in the development of this direction was played by the use of **finite element numerical simulation (FEM)**. Three-dimensional models of industrial components were developed, allowing:

- the analysis of stress distribution in areas with geometric variation;
- the assessment of the effect of stress concentrators generated by discontinuities, fillets, or assemblies;
- the simulation of cyclic loading regimes and cumulative stress effects;
- the analysis of behavior under limit conditions.

Through numerical simulation, critical areas susceptible to damage initiation were identified, and based on the obtained results, constructive optimization solutions were proposed. These solutions included the modification of local geometry in order to reduce stress concentrators, the optimization of dimensions, and the selection of materials with superior behavior under cyclic loading.

Furthermore, numerical simulation enabled the assessment of the influence of technological parameters on in-service performance, facilitating the optimization of manufacturing processes and the reduction of structural defects. The integration of numerical analyses into the design phase contributed to the development of the concept of **"reliability-oriented design"**, by anticipating critical areas prior to the physical manufacturing of components.

The obtained results demonstrated that reducing stress concentrators and optimizing load distribution lead to increased durability and improved in-service performance of industrial mechanical systems. In specific applications from the energy and extractive industries, the developed methods provided the basis for technical decisions regarding equipment modernization and operation, contributing to the reduction of failure risk and the increase of operational safety.

Through the integrated approach—**theoretical analysis, numerical modeling, and industrial applications**—this research direction led to the development of useful methodological tools for assessing and optimizing the reliability of mechanical systems, thereby consolidating the scientific profile in the field of durability and in-service behavior of industrial equipment.

In the field of **quality management**, the research focused on the integration of modern tools for quality assurance, control, and continuous improvement within engineering projects and industrial applications, in accordance with current requirements regarding performance, traceability, and process sustainability. The adopted approach aimed to correlate the technical dimension of products and processes with the performance indicators specific to quality management systems.

Methodologies were developed for the application of **statistical process control (SPC)** tools, process capability analysis, and the use of root-cause analysis methods for nonconformities. The integration of these tools into engineering projects enabled the monitoring and reduction of variability in technological processes, the optimization of manufacturing parameters, and the increase in the stability of industrial processes.

Particular emphasis was placed on correlating technical indicators (dimensional tolerances, stress distributions, functional parameters) with process performance indicators (defect rate, cost of non-quality, operational efficiency). Through this integrated approach, a direct link was established between engineering analysis and quality management, contributing to the substantiation of technical decisions on a quantifiable basis.

At the same time, the research aimed at developing the **educational and experimental infrastructure** necessary for training specialists in the field of Industrial Engineering. Teaching and research laboratories were modernized, software applications for simulation and statistical analysis were introduced, and practical activities were correlated with real industrial problems.

This infrastructure enabled the integration of the concepts of Quality Management, reliability, and process optimization into university and doctoral training activities.

The thesis also highlights **interdisciplinary contributions** in the fields of industrial engineering, sustainability, and occupational safety, structured along two main directions: the development of mechanisms generating aesthetic curves and innovation in the reduction of pollutants and environmental impact.

One research direction concerns the development of mechanisms capable of generating aesthetically appealing geometric forms, taking as its model the **"Flower of Life,"** a geometric symbol with profound historical and mathematical significance. The study proposes two original mechanisms—one based on the **Geneva mechanism** and the other on **compound-profile gears**—capable of reproducing this structure through kinematic synthesis and closed-loop analysis. The integration of programming made it possible to validate the generated trajectories, demonstrating the potential of these mechanisms in industrial and design applications (textiles, architecture, industrial design). The research contributes to outlining a new subfield in mechanism theory: the generation of aesthetic curves.

In parallel, **bio-inspired mechanisms** are analyzed, particularly gripping and locomotion mechanisms with applications in robotics. Studies on bird biomechanics highlight efficient solutions for grasping and stability, based on geometric adaptability and energy consumption optimization. The developed equivalent mechanical models provide relevant perspectives for the design of robots capable of operating in complex environments.

Another research direction addresses **industrial sustainability** through the perspective of **green supply chain management (GSCM)** and **green innovation (GI)**. Based on a meta-analysis of recent studies, it is shown that GSCM practices significantly contribute to improving environmental performance and achieving carbon neutrality, with effects influenced by the economic and institutional context. The integration of the **Resource-Based View (RBV)** and the **Natural Resource-Based View (NRBV)** highlights the strategic role of environmental capabilities in achieving sustainable competitive advantage.

Another important aspect concerns the **assessment of chemical risks in industrial processes**, particularly in welding. Experimental analyses indicate exceedances of permissible limits for certain types of emissions, confirming the existence of a high chemical risk and the need to implement rigorous preventive measures. The methodologies used include substance inventory, risk ranking, and environmental impact assessment. In the case of manual electric arc welding with coated electrodes, the results show that, under controlled conditions, emissions can be maintained below the admissible limits.

Overall, the presented research contributes to the development of innovative engineering solutions through the combination of aesthetics and functionality, the integration of bio-inspired principles, and the promotion of sustainability and safety in the industrial environment.

The **technology transfer** activity is reflected in active participation in national and international research projects, as well as through applied research contracts with economic operators. These projects aimed to solve concrete problems related to equipment durability, the optimization of technological processes, the reduction of failures, and the improvement of operational performance.

The implementation of research results in the industrial environment involved validating technical solutions under real operating conditions, developing applied methodologies, and formulating technical recommendations for equipment modernization. Through these activities, fundamental research on contact mechanics, reliability, and process optimization was translated into concrete technological solutions, with a direct impact on the economic performance of industrial partners.

This applied dimension highlights the ability to integrate theoretical and numerical research into projects of practical relevance, demonstrating the competence to generate innovative solutions adapted to industrial requirements. At the same time, constant collaboration with the economic environment contributed to strengthening the **university–industry relationship** and increasing the visibility and impact of scientific activity.

By correlating quality management with engineering research and by capitalizing on the results in industrial applications, an integrated approach has been outlined that supports both technical performance and economic competitiveness, thereby strengthening the academic profile in the field of Industrial Engineering.

Future research directions will aim to consolidate and extend the developed theoretical and applied framework through multidisciplinary approaches and the use of advanced modeling and monitoring technologies.

A priority direction consists in the development of advanced **three-dimensional finite element models** for the analysis of fretting contacts under real operating conditions. These models will integrate nonlinear contact, friction dependent on pressure and relative speed, and the progressive evolution of damage. Explicit modeling will be pursued for partial and gross slip regimes, stress redistribution under cyclic conditions, and the influence of surface microgeometry on the overall behavior of the contact. The implementation of three-dimensional models will enable a detailed analysis of volumetric stress distribution, the identification of subsurface areas susceptible to crack initiation, and the assessment of the effects of geometric and mechanical parameters on durability.

In parallel, the integration of **elastoplastic-viscoplastic material behavior** into numerical models will be pursued. This approach will allow a realistic description of strain hardening, stress relaxation, and the progressive accumulation of plastic strains under cyclic loading. Viscoplastic modeling will be essential for the analysis of components operating at elevated temperatures or under complex loading regimes, where time-dependent effects become significant. The integration of these constitutive models will contribute to increasing the accuracy of predictions regarding the transition between wear, fatigue, and severe plastic deformation regimes.

Another major direction concerns the development of **probabilistic models** for estimating the service life of mechanical components. In this respect, the integration of variability in material properties, loading conditions, and contact parameters into a statistical framework for reliability analysis will be pursued. The use of probabilistic methods (**Weibull distributions, Monte Carlo methods, hazard-based models**) will allow the assessment of failure risk and the determination of remaining useful life under uncertainty. This approach will facilitate the transition from deterministic durability assessment to a **risk-oriented approach**, with direct applicability in industrial maintenance.

In line with current industrial digitalization trends, future research will integrate **Industry 4.0 technologies** into the monitoring and predictive maintenance of mechanical systems. The use of intelligent sensors for monitoring vibrations, temperature, and operating parameters will be pursued, together with the development of **digital twin** models for real-time behavior simulation and the implementation of predictive analytics algorithms for anticipating failures. Correlating experimental data obtained during operation with the developed numerical models will enable the optimization of maintenance strategies and the reduction of downtime.

By integrating advanced three-dimensional modeling, nonlinear material behavior, probabilistic analyses, and digital technologies, future research directions will contribute to the development of a modern scientific framework for the assessment and optimization of the durability of mechanical systems.

Overall, the theoretical, numerical, and experimental contributions presented in the thesis highlight the attained scientific maturity, the ability to address complex problems in the field of Industrial Engineering, and the competence to develop and coordinate advanced research activities. At the same time, they demonstrate the potential to establish and consolidate a **doctoral school** focused on the durability, reliability, and in-service behavior of mechanical systems, in accordance with current requirements of scientific research and the industrial environment.

The final chapter of the habilitation thesis outlines a **strategic program for the development of scientific activity** in the field of Industrial Engineering, grounded in the research experience accumulated and in the results obtained in areas such as fretting, the durability of mechanical systems, quality management, and technology transfer. The proposed directions aim both at consolidating an individual research line and at developing a competitive doctoral school, with an impact on academic visibility and university–industry collaboration.

A first major direction concerns the deepening of fundamental and applied research on the fretting phenomenon, regarded as a complex damage mechanism with significant effects on the service life and safety of mechanical components. The development of three-dimensional numerical models, elastoplastic-viscoplastic models, predictive criteria for service life estimation, and studies on crack initiation and propagation is proposed. These investigations will be complemented by parametric analyses, constructive solutions for reducing fretting, and experimental validation, with direct applicability in the energy and mining industries.

The second strategic axis is dedicated to increasing the durability and reliability of mechanical systems by developing modern methods for degradation assessment, predictive service-life models, and tools based on numerical simulation. At the same time, technological solutions for increasing durability and implementing predictive maintenance concepts are envisaged, with the aim of reducing operating costs and increasing operational safety.

Another important direction concerns the development of research in the field of **quality management and industrial product development**. A transition toward integrated and intelligent quality management systems is proposed, through the correlation of international standards with risk management, process management, environmental management, and occupational safety. In this context, digitalization plays an essential role, involving concepts such as **Quality 4.0**, digital traceability, the use of artificial intelligence, intelligent sensors, and cyber-physical systems. Directions are also included regarding process optimization, increased product reliability, and the development of innovative, sustainable, and high-performance products.

The chapter assigns particular importance to **technology transfer and collaboration with the economic environment**, considered essential for the practical valorization of research results. In this regard, the development of durable partnerships with economic operators, the implementation of applied research contracts, the development of innovative products and technologies, the transfer of results into industry, and, in the medium and long term, the establishment of a research and technology transfer center within the university are envisaged.

A central strategic objective is the consolidation of an independent research direction and the training of **highly qualified human resources**. This involves attracting and supervising doctoral students, involving undergraduate and master's students in research activities, developing experimental and numerical infrastructure, participating in national and international projects, and publishing results in prestigious journals. The aim is thus to establish a research school in the field of fretting and the durability of mechanical systems, with national and international recognition.

In accordance with these directions, three doctoral research axes are proposed: the study of the fretting phenomenon and the durability of mechanical systems, the reliability and maintenance of industrial systems, and quality management and the development of industrial products.

Overall, the chapter proposes a coherent, modern, and sustainable vision of the evolution of the scientific career, based on the integration of fundamental and applied research, alignment with **Industry 4.0** trends, and the strengthening of the relationship between the university and the socio-economic environment. The implementation of these directions is intended to contribute to the affirmation of a distinct scientific profile and to the enhancement of the academic prestige of the **Constantin Brâncuşi University of Târgu Jiu**.

The experience accumulated over more than **30 years of academic and research activity** in the research fields in which I have been active has been capitalized on through the publication of scientific papers, projects, and contracts. This experience will continue in the future along new research directions, which the author has presented in the final part of the habilitation thesis.