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Axa prioritară 1 „Educaţie şi formare profesională în sprijinul creşterii economice şi dezvoltării societăţii bazate pe cunoaştere”

Domeniul major de intervenţie 1.5. „Programe doctorale şi post-doctorale în sprijinul cercetării”

Titlul proiectului: „Armonizarea valenţelor academice româneşti cu cele ale Comunităţii Europene”

Cod contract: POSDRU/CPP107/DMI1.5/S/76851

Beneficiar: Universitatea „Lucian Blaga” din Sibiu

Ing. Lucian Eugen ROŞCA

TEZĂ DE DOCTORAT

THE COLLABORATIVE PLATFORM FOR PARAMETRICAL ANALYSIS OF MECHATRONIC SYSTEMS

Conducător științific: Prof.Univ.Dr.Ing. Ioan BONDREA

Sibiu

-2015-

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ABSTRACT

Introduction

The design and development of the mechatronic systems uses different domains of engineering such as: mechanics, electronics, automatics and software control. The high number of engineering domains involved in developing of a single product brings to forefront the problem of organizing and interdisciplinary collaboration at the different stages of the development. The collaborative methods of design and development become more and more important in view of reducing the time to obtain the final prototype, ready for production. In order to allow supplementary synergies between the engineering domains which contribute to the development of a single mechatronic system, the engineers from all the fields involved in development would have to adopt new work methods that facilitate interdisciplinary collaboration in an integrated manner.

The present thesis **"The Collaborative Platform for Parametrical Analysis of Mechatronic Systems"** addresses the subject of development of a complex mechatronic product where any change of a parameter belonging to a component can influence the system's performance.

General aspects

Starting from the analysis of the current status of technologies and software instruments used in the design and development of mechatronic systems, the following objectives of the present PhD thesis can be defined:

The general objective is the conception, development and implementation of a collaborative platform for parametric analysis incorporating new development techniques in the design and development of mechatronic systems.

Specific objectives:

1. Study on development models in the domain of design of mechatronic systems and on the existing theoretical progress in the development of collaborative platforms for design and development.
2. Study of mechatronic systems currently adopted in the automotive industry and of the current state of systems under development and in the process of adoption.
3. Theoretical research on collaborative platform for parametrical analysis that primarily aims to contribute at the increase of collaborative inter-disciplinary character for the development cycles at both macro and micro level.
4. Research on the conceptual design at the level of defining system functions under the proposed parametric analysis platform.

   a) Research on the electronic braking system of passenger vehicles by implementing a data acquisition system for recording the signals measured on the sensors of vehicles under observation.

   b) Implementation of processing algorithms of acquired data using the programming environment MATLAB for statistical analysis used to obtain high certainty information on the mode of operation and actual operating conditions.

   c) Research on the recovery function for braking energy where a parametrical analysis is performed and definition of constraints.
5. Research on the stage of integration, validation and testing of the system functions under the proposed parametric analysis platform.

a) Detailed analysis of the electronic braking system (mechanical, hydraulic and electrical / electronic components) and analysis of ABS function (Anti-lock Braking System) from the point of view of the control logic and mechanical and hydraulic architecture.

b) Electronic Brake System modeling and ABS function modeling.

c) Evaluation of the impact of tolerances due to mass production of components that compose the braking system, as well as analysis of the influence of external parameters during operation. The validation of the tolerance of the system through and its analysis is done using brake system model and Monte Carlo simulation technique.

6. Research on the detailed design stage under the proposed parametric analysis platform.

   a) For the micro level development (component level) is established as an objective the analysis of current research in the field of CAD modeling and simulation using finite element method for electric motors.

   b) CAD design using CATIA design environment for a DC electric motor component of the braking system and activation device for the hydraulic pump.

   c) Use of CAD geometry for numerical simulation using finite element method and software COMSOL-Multiphysics to analyze the design constraints defined in previous stages under the collaborative platform of parametric analysis.

7. Drawing conclusions on the interdisciplinary collaboration through the use of the collaborative platform for parametric analysis, at the stages of development of mechatronic systems, for the different cycles of the development process: the overall cycle of development at the macro level, macro-cycles depending on the degree of maturity and process modules specific with recurrent character at the stages of solving problems at the micro level.

Structure and content of the PhD thesis

The PhD thesis is structured in 7 chapters presented in 173 pages without annexes (207 pages with annexes), 163 pages without bibliographic references, and 108 references

Chapter 1, "Introduction" presents the general aspects relating to the proposed study of this thesis. The first part the theme is described and justified, starting from the idea of increasing labor productivity and ease of the work of the engineers in the car manufacturing industry. Further main objective of the thesis is defined still the: design, development and implementation of a collaborative platform for parametric analysis incorporating new development techniques in the process of design and development of mechatronic systems tailored for the automotive industry, particularly for complex mechatronic systems. Seven specific objectives are defined.

In Chapter 2, entitled "Models for design and development of mechatronic systems - current state", the aspects regarding particularities of design models of mechatronic systems are summarized. At the same time, the types of mechatronic systems adopted in the automotive industry and implementation stage to the so-called "by-wire" systems are identified. This chapter highlights on the one hand the trend of increasing complexity for most of mechatronic systems in automobiles and industry and on the other hand the need to develop research on the establishment of structured models for developing mechatronic systems with the aim of exceeding the flexibility limits achieved through the current methods. At the end of this chapter current issues needed to be resolved by means this research are defined.

In Chapter 3, entitled "Proposal for a collaborative platform of parametric analysis of mechatronic systems in the automotive industry" an improved model for development of mechatronic systems is proposed. Compared to the standard VDI-2206, the proposed model specifies the presence of a simulation activity and a parametric analysis at the level of the conceptual design of the system functions, both for the conceptual design stage and the stage of integration and verification. This model seeks to define a design platform specific to the development of mechatronic systems in the automotive industry, which aims to increase the collaborative character, i.e. the communication between different areas of engineering at macro and micro level of development, by defining design constraints based on various analysis of parameters (internal and external) in a coordinated way and two-way communication between levels of development.

In Chapter 4 of this thesis, entitled “Contributions to the conceptual design at the level of defining mechatronic system functions”, it is selected as a case study the function of braking energy recovery of an electronic braking system for passenger cars. Research on analysis of operating parameters for the electronic braking system take place by implementing a data acquisition system for recording signals measured on the vehicle sensors. Post-processing of data is accomplished by implementing a statistical analysis algorithms using MATLAB programming environment and the results generated are synthesized by means of histograms and diagrams with high certainty on operating cycles and real operating conditions of vehicles.

Before beginning the detailed design phase of the development, the specific constraints related directly to external operating parameters in real environment are established at this level. This study of analyzing operating parameters determines the definition of constraints for the following stages of development, such as: minimum and maximum limits where the system must fit so that the proposed functions have maximum efficiency; determining the rate of activation of certain functions (impact on the system), estimating the wear; defining testing parameters.

For the function of recovery of braking energy and based on analyses of operating parameters, in this research it is demonstrated how the specific constraints are identified (speed range and level of deceleration) for which the system must be sized so that energy recovery is most efficient.

In Chapter 5, entitled "Contributions regarding the stage of integration, validation and testing of the system functions", within the collaborative platform proposed, it is exemplified the validation of the braking function of ABS (Anti-locking Brake System) form the point of view of quality assurance. In the beginning the architecture of braking system and the ABS function are presented. Further, the creation of the mathematical model of the system starts from the identification of its sections (mechanical, hydraulic, electronic and control), where each component's tolerances are listed and their values established as input parameters for the model. Afterwards, the evaluation steps are established, so that two types of analysis are chosen, one for the nominal values of the parameters (according to design) and the second one using the Monte Carlo simulation (input parameters chosen randomly). The simulation results show the influence of tolerances due to mass production on the system's performance for a fixed sample of units produced. Research in this section serves to illustrate the techniques by which the validation of the functions of a mechatronic system can be made at the integration stage using the simulation technique and the constraints defined in the earlier stages of development.

Chapter 6, entitled "Contributions to the detailed design of mechatronic system components" refers to the use of constraints defined in previous levels of design, in order to be validated or modified by performing several cycles of simulation analysis at the micro level. The simulation activity specific to engineering is an integral part of the implementation process for the detailed design phase at the level of the development of components. The collaborative platform places the simulation activity in direct relation to the use of specific constraints as input data.

In this chapter, the detailed design is applied to one of the main activation components of the brake system, i.e. the DC electric motor acting the hydraulic pump. The first part of this chapter presents the mathematical model for obtaining the dynamic characteristics, where the implementation is done using MATLAB simulation environment - Simulink. Also, its 3D CAD design is presented, its building elements and the types of material. Finite element simulation is performed using COMSOL-Multiphisics platform and CAD 2D geometry of the motor. The results obtained in this chapter show the effect of temperature on the torque developed by the motor considering that its variations can have major impact on the performance of the entire braking system.

In the Chapter 7, entitled "Conclusions, personal contributions and new research directions", the final conclusions, the own original contributions, the scientific results from the study (list of publications) and the future research directions are presented. This thesis, through the studies and the research done, proposes an improvement in the standard model VDI-2206 for developing mechatronic systems, by using the collaborative platform of parametric analysis model that extends the simulation and analysis activity at the level of the definition of system functions, both at the conceptual design stage and at the integration verification and testing stage.

The methodology and research stages

Based on the proposed objectives and on the critic analysis of the theoretical and experimental achievements in the development models for mechatronic systems, a classification of the models was carried out according to the level of the inter-disciplinary collaboration both at micro and macro level using three main criteria: parallel design, cooperation at macro level and cooperation at micro level. At the same time, the performed studies highlighted that modeling and simulation play an important role, as an integral part of the development process. Computer-assisted (specialized software) design modeling and simulation have developed in response to the need to streamline the product development process, in particular the complex ones. By means of simulation we can study the behavior of different types of systems with a view of making decisions on their future improvement. Designing, modeling and simulation of systems by means of dedicated software shortens the time needed for obtaining optimal solutions, allows analysis of a large number of possible variants by modifying model parameters and has the advantage of ease of return to the version with results nearest to the technical requirements. Simulation is present for all areas involved in development of mechatronic systems mechanical elements and kinematic model creation, hydraulic models, electrical system modeling, modeling and simulation of control logic.

Based on the findings of the current state, a model of a collaborative platform for parametric analysis is proposed for the development of mechatronic systems that will support increasing the efficiency level of development by reducing the time required for design, where the current trend is one of increasing complexity due to the number of components linked in a complex architecture, for most systems under development in the automotive industry.

As part of the collaborative platform, the research on the analysis of operating parameters for electronic braking system takes place by implementing a data acquisition system for recording signals measured on vehicle sensors. Post-processing of data is accomplished by implementing a statistical analysis algorithms using MATLAB programming environment and the results generated are synthesized in histograms and diagrams with high certainty on operating cycles and real operating conditions of vehicles.

The theme of quality assurance in mass production is covered in the validation and testing phase of the system functions. The electronic braking system comprises of a high number of components linked in a complex architecture so in order to analyze the impact of the tolerances of these components on system performance a Monte Carlo simulation was adopted. At the same time, this study analyses the external disturbing factors that appear during the functioning of the system. The Monte Carlo simulation is an iterative method of assessing models that uses as inputs sets of random numbers. This method is used for the ABS brake function which involves a number of variables, in particular tolerances of the mechanical, electronic and hydraulic parts. The implementation steps are as follows:

- Modeling of braking system and simulating of ABS function starting from the feature of activation of the ABS valve of current vs. pressure.
- Setting the input parameters by setting the tolerances' probabilistic for each component.
- Establishing of external parameters by using the tolerances' probabilistic distributions of temperature, voltage and consumption.
- Simulation of different possible conditions both relating to production and exploitation.

The research results are relevant for the quality control of the system functions (determining the impact of tolerances on performance) in addition to providing the opportunity for further optimizations by changing tolerances, which can be done based on this research so as it be determined the maximum value of the deviations that can be accepted for certain components without making a compromise on the system's performance.

The subject of detailed design at the level of the system components is applied to one of the main components that activate the brake system, i.e. DC electric motor that activates the hydraulic pump. The use of the analysis method of finite element is adopted in order to developing of a component at micro-level during the detailed design stage, method on which the industry research and development relies with predilection.

The modeling and simulation of DC motor, the brake system component used in the hydraulic pump activation, was conducted as part of the research. The aim is to use the defined constraints at various higher levels of design as input data for parametric analysis, with the results indicating their influence on the electro-magnetic torque developed by the motor. The objective of this research is to model and simulate the magnetic effects that occur during the operation of the electric motor and whose variations contribute to changes in the performance of the studied system.

The research conducted in this work were aimed at increasing the level of knowledge in the design of mechatronic systems in the automotive industry by using various different modeling techniques and simulation methods adapted to solve specific problems in the industry today.

The research developed during the preparation of the thesis has a theoretical and practical application, defined by completing successive stages of the theoretical research followed by an implementation example to demonstrate the functionality of the collaborative platform for parametric analysis proposed as a development model for mechatronic systems in the automotive industry.

Addressing the chosen theme determined the need to identify best practices (working methods) that can be integrated into a collaborative platform for parametric analysis that links results from different stages of development and that contributes to a better identification of solutions for optimization.

Collaborative platform for parametric analysis - proposal

The collaborative platform for parametric analysis for mechatronic systems in the automotive industry is based on the development standard for mechatronic systems VDI 2206. In contrast to this, the proposed platform changes the two branches (conceptual design and integration and verification) adding new elements for development at the macro level (figure 3.1). It is therefore required:

- A parametric analysis and simulation process present at all levels of design for both development branches: conceptual design and integration and verification.
- For each level of development a definition of system / subsystem / component constraints, based on simulation and analysis results.

- The sum of constraints in the conceptual design stage is in this way consistent and correlated with all higher levels, being used as input data for the implementation phase (detailed design)
- To include at each level of the integration phase the specific testing and verification activities present in VDI 2206 as well, but also add to the proposed model a simulation and analysis process for system's parameters for each separate level.
- To use the tests and simulations results performed at each integration level to modify the constraints defined in the preceding stages of development in order to achieve the requirements imposed.

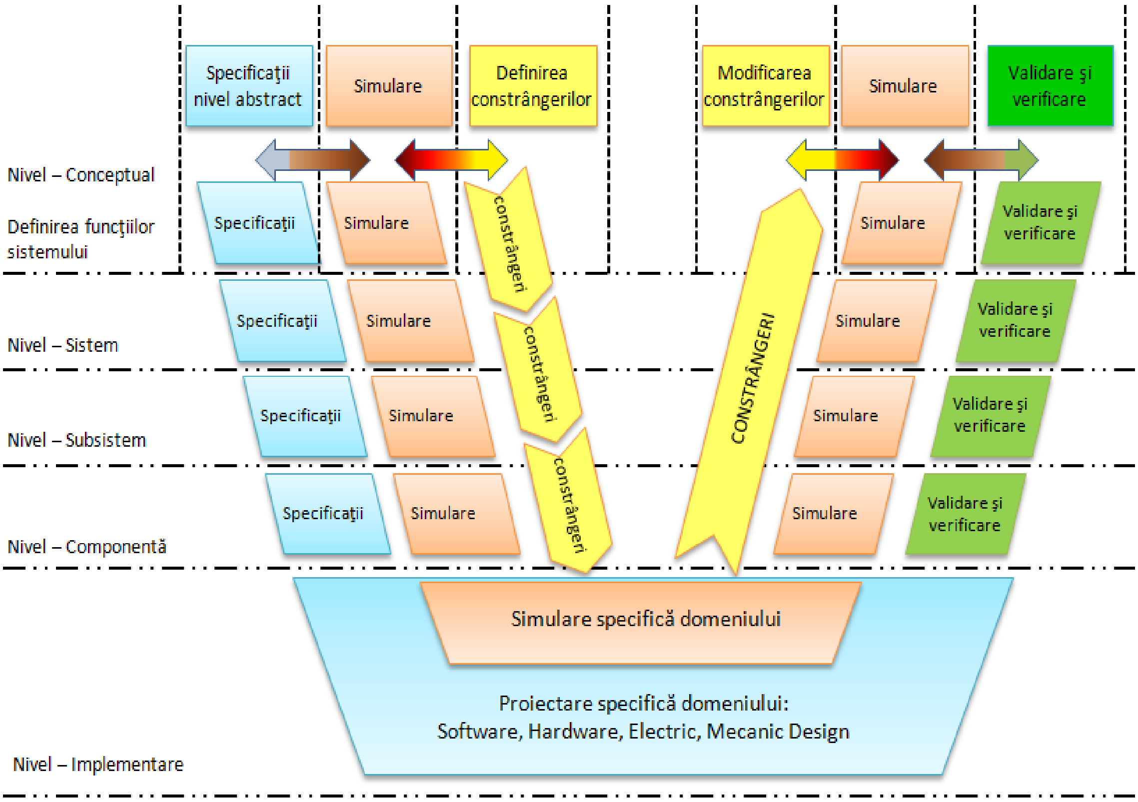

Figure 0.1 Proposed design model

Compared to the standard VDI 2206, the proposed model specifies the parametric analysis at the conceptual definition levels of the functions, of the entire system and for the validation and verification. Moreover, the communication between different levels of design is possible for macro-level design by defining system constraints. This is used for communication between the levels of development by analyzing the parameters of the system to be developed but also for the communication between different disciplines of engineering.

This model aims at defining a design standard specific to the development of mechatronic systems in the automotive industry. It aims to increase macro-level communication between the different areas of engineering by analyzing various parameters (external system) at all levels of development and defining constraints in a collaborative and bi-directional propagation between levels of development. For example, in the automotive industry the following are identified as important parameters:

External parameters:

- Driver's influence through the driving mode (sport or normal driving mode)
- The rate of urban/ extra urban exploitation which implies a certain speed regime given also by the infrastructure type (highway, highway, urban driving)
- Temperature in the geographical area where the vehicle is exploited can influence the wear level/ km

System parameters:

- Mechanical components - design parameters and material
- Electrical / electronic components - normal operation parameters

- Software - normal operating parameters have limitations directly related to the operating temperature, mechanical and electromechanical response to the controls implemented in the software programme.
- Manufacturing tolerances - tolerances parameters that can affect system performance and functions

From the few examples listed above it can be observed the two major classifications, external parameters (disturbance) and system parameters (technical parameters). They can influence the period of development since the early system design stages, i.e. the number of macro cycles performed to arrive from a laboratory prototype to a system with a high degree of maturity ready for production. The different engineering fields that make up a mechatronic system and their specific parameters can also be observed. The better known, classified and inter-connected on levels and disciplines the parameters are, the fewer macro-cycles may result through a rigorous definition of constraints. Figure 3.2 shows the model developed in a linear form, from the top down to reveal the stage of defining constraints the form of a matrix which represents:

- The lines represent the division on development levels (the system functions, system, subsystem, implementation, integration and validation)

- The columns represent the constraints specifically defined for each design domain

- The change of constraints occurs in the final step, following the integration of all elements of the system and of the testing and validation of the system.

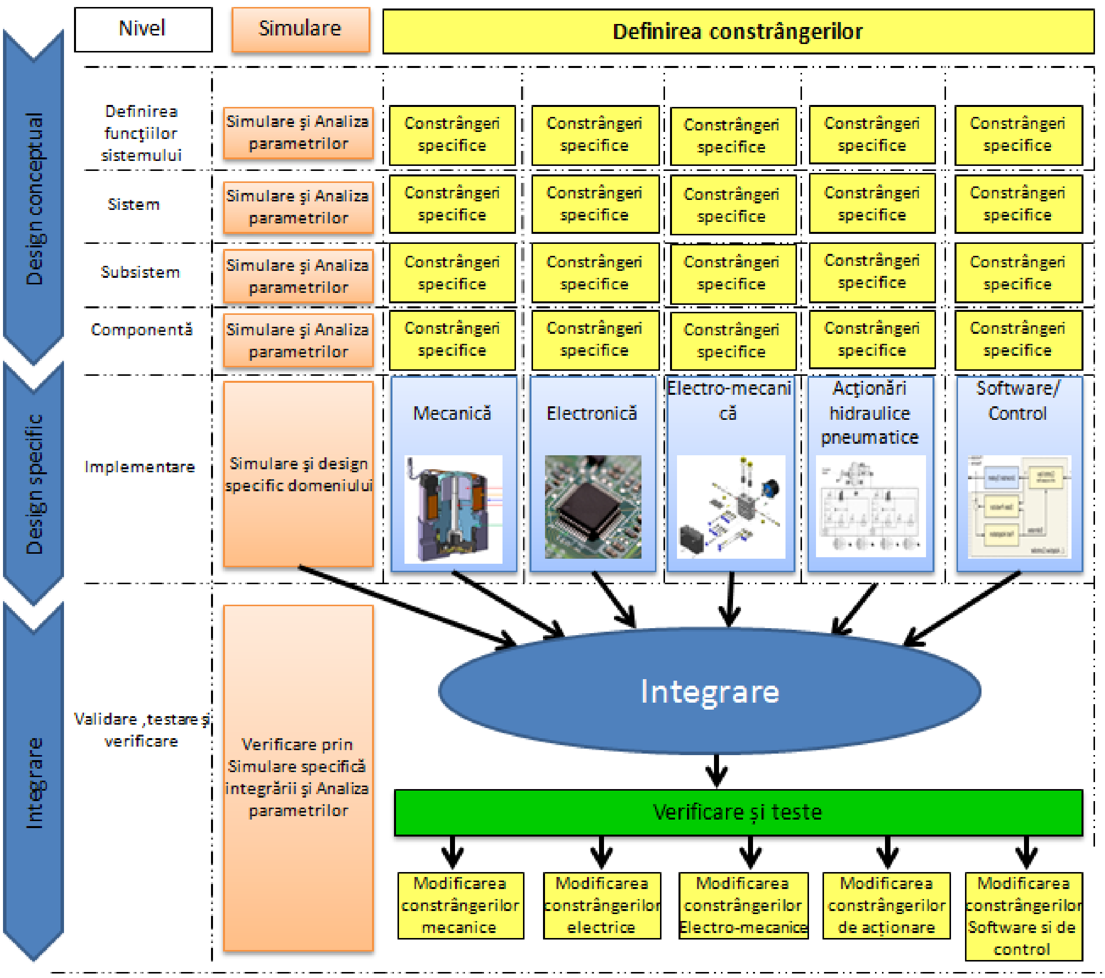

Figure 0.2 Constraints matrix of the development model

Compared to the VDI 2206 classic model, the proposed model includes the following new elements:

- The introduction of the parametric analysis activity for the conceptual design level of the system's functions and related feasibility study.
- The defining constraints as a correlated branch to the simulation and parametric analysis activities for all levels of development.

- The introduction of the simulation activity in the integration and validation phase for all levels and all specific domains.
- The amendment and adaptation of constraints to find the best compromise to further optimization (route through a new macro cycle)

Conclusions, contributions and new research directions

To date, many efforts have been made to create design models and related software support that will benefit by improving inter-disciplinary communication in the mechatronic system design. However, after evaluating various design models in terms of facilities for collaboration between different fields of engineering that they provide, some weaknesses in collaborative multi-disciplinary at the management level of information exchange between different engineering areas and the lack of integrated software tools are apparent. The main question that this paper answers is: How can one improve the design of mechatronic systems for faster and more efficient industrial development? Since the beginning, the collaborative platforms were designed for the integration of several areas of engineering under the same design model.

This PhD thesis has a multidisciplinary, being built based on concepts from domains such as design of mechatronic systems, mathematics, physics, electro-mechanics, statistics, modeling and simulation.

With an aim to improve the design and development processes of mechatronic systems in automotive industry, the implementation and use of a platform for parametric analysis with a collaborative specificity between different areas of engineering is proposed. This is based on the standard model for developing mechatronic systems VDI2206. Thus two parametric analysis methods are designed, developed and implemented for the conceptual design level, both for the development of mechatronic system functions and for testing and validation during a macro development cycle. Also, the paper presents the contributions of the platform for parametric analysis related to the development at the detailed design level. To validate the proposed platform, the case study is conducted on the electronic braking system for passenger vehicles for the braking energy recovery function and for the ABS function. The techniques proposed use data acquisition methods, statistical analysis algorithms, Monte-Carlo simulation, finite element simulation and CAD design.

In this paper makes contributions to the development of design methods of mechatronic systems by increasing the inter-disciplinary collaboration at micro and macro level (example applied to a mechatronic system) by adopting different design techniques in a collaborative working process so as to introduce a more effective way of working. The thesis is using a model focused on centralizing information on the parameters of a mechatronic system and facilitates the use of information in a coordinated and consistent way meant to easily identify optimal decisions. It also improves the quality of the design process, making it possible to reduce the number of experimental tests needed to put a prototype in series production.

As a first step of the research the dynamic behavior and operating cycles are analyzed for a fleet of six cars under observation, and then research is extended to an analysis of the braking system. Data acquisition system for measuring physical signals is composed of specific electronic equipment connected to the CAN-BUS communication network of the vehicles. The data acquired are then processed using an analysis algorithm developed in MATLAB using two types of histograms for detailed highlighting of the results. Brake energy recuperation function is evaluated as a possible new system functionality. For this a parametric analysis is performed and constraints defined by identifying the optimum interval for kinetic energy recovery.

The thesis continues with the analysisof the impact of tolerances on performance of ABS function of the braking system for validation and testing phase. Tolerances due to serial production, plus the impact of external disturbing factors, may adversely affect the system's performance. In terms of quality assurance it is desirable to know the percentage of non-conformity for a representative sample of systems produced. To this end, the brake system model is developed including all its components (electrical, mechanical and hydraulic) and the variation range for each parameter is defined, together with the corresponding probabilistic distributions. Then the tolerances analysis is carried out by using the probabilistic simulation technique Monte Carlo under different operating conditions.

In the collaborative platform for parametric analysis the detailed design stage and development at the system's component level is also addressed. To this end CAD designing using CATIA V5 was done for a DC motor, as a component of the braking system used to activate the hydraulic pump. The parametric analysis is performed by modeling and simulation using MATLAB - Simulink, but also by means of an advanced model using finite element method and simulation environment COMSOL - Multiphysics. The aim was to demonstrate the feasibility collaborative platform using the defined constraints at various higher levels of design. The analysis results show the influence of parameters on the electro-magnetic torque developed by the motor. The torque variation contributes to changes in system performance, the parameter engine will be modified by changing the constraints or maintained by validating them.

Contributions

This thesis has an innovative character bringing a series of original contributions regarding the main stages of development of mechatronic systems in the automotive industry.

Based on a research methodology which covers various aspects relating to the purpose and objectives of the thesis, following the investigations performed and the results obtained the following contributions are synthesized:

1. A critical analysis of the current models of design of mechatronic systems and the current level in development of collaborative software design platforms for different disciplines and engineering fields.
2. An analysis of the current state of mechatronic systems in the automotive manufacturing industry with emphasis on new technology "by-wire" and on the electronic braking system for the modern car.
3. Proposal of a multidisciplinary collaborative platform based on development standard for mechatronic systems VDI 2206 by adding of interdisciplinary communication elements at the macro level of the development cycle and exemplifying the use of the model for of different levels of development both for the design branch and for the integration and validation.
4. Defining of the parametric analysis method for conceptual design branch at the system functions level for the braking energy recovery function. The analysis is based on processing and interpretation of data acquired from vehicles in operation, such as, by means of statistical analysis methods, the design constraints can be identified, leading to optimal design of the system starting since the early development to avoid making many macro design cycles. In the

example used the optimal interval for brake energy recuperation was identified on a statistical basis depending on the mode of operation of the vehicles under observation.

5. The design and parametric analysis for the integration, verification and testing branch at the level of system's functions for quality assurance by assessing the impact of tolerances due to mass production of the components that make up the mechatronic system (mechanical, hydraulic, electric and electronic)
6. Exemplifying of the use of constraints defined at different levels (system / subsystem / functions) for the detailed design stage.