CONSTANȚA MARITIME UNIVERSITY
Doctoral School of Mechanical Engineering

HABILITATION THESIS

HYBRID MODELING IN MECHANICAL ENGINEERING

MODELARE HIBRIDĂ ÎN INGINERIA MECANICĂ

Abstract – excerpt from the habilitation thesis

Associate Professor PhD Eng. Emil M. OANȚĂ

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A. ABSTRACT

The habilitation thesis includes the concepts, the results and the ideas achieved along more than three decades of scientific research in mechanical engineering using computer based methods, especially original software instruments as principal means of investigation.

First research studies started during my undergraduate studies when I was involved in the scientific research projects of my professors. My mathematical solutions and implementations of the geometry related models were highly appreciated at the students' scientific conferences and by the completion of the undergraduate studies I was co-author of 7 scientific papers together with my professors, papers presented by me at National Conferences of the professors and researchers. Other accomplishment was the participation to the creation of a book where two of my programs were published. After graduation in 1988, I worked two years in a computer office where I started the development of the first software projects which helped me in the first computational mechanics projects.

Starting with 1990 I was assistant professor (tenure track) and from 1991 assistant professor. In 1994 I became lecturer and from 2002 I am associate professor. During 1990-1991 I participated to the Experimental Mechanics course held in the Strength of Materials Department of the Polytechnic Institute of Bucharest by a group of great professors to whom I express my gratitude. Experimental mechanics was a new field and I understood that the experimental studies are paramount in the context of a research project. This was a new field I embraced and I participated 'hands-on' in several experimental projects for industry. I also participated to several science project and I realized that the data resulted from the various studies was used either as input data for other studies, or to verify the results of other studies.

The first PhD is in Mechanical Engineering and my promoter was professor Dinu Taraza, who strongly advised me to start an experimental project for industry as a backbone of my future thesis. I succeeded to complete the complex experimental study at "Master SA" in Bucharest, i.e. the former "National Institute of Thermal Equipment". After he became a professor at Wayne State University in Detroit I presented at the SAE 2000 Congress the results of the experimental study and I am very grateful to professor Dinu Taraza for mentoring me and for offering me new horizons in science and in life. Starting with 1998 my new promoter was Prof. Dr. H.C. Constantin Aramă, member of the Romanian Science Academy, another great professor who guided me in the final period of the PhD thesis which was rated as 'Cum Laude'.

After the completion of my first PhD thesis in 2001, I understood that the high complexity of the projects, no matter the field of science, must have similar solutions which, further on, have themselves a common denominator. Moreover, in this context, the experimental studies are very important in order to verify the theoretical models, so they should also have an important role in the context of the 'similar solutions'.

The second PhD started in 2001 at the Faculty of Economic Cybernetics, Statistics and Informatics from the Academy of Economics Studies of Bucharest. It helped me understand the complexity of the economic models which were based on probabilistic and stochastic formulations, update my knowledge in computer programming, participate to the LASCOT, ITEA-type project and meet new great professors. I am grateful to professor Ilie Tamaș who advised me over two decades in computer programming and to professor Ioan Odăgescu, the promoter of my second PhD thesis, completed in 2007. By the end of this PhD a new idea was emerging: to integrate the results of the various types of studies belonging to distinct fields of science.

Starting with 1990 I also acquired experience in several fields of engineering because I helped my colleagues with the implementations for their PhD theses, which was a great

opportunity for me to learn more regarding the mathematical background of their solutions and regarding the implementation of the according original software solutions.

The idea to include the various types of studies of a project, which was persistent over the years, in an upper overview level led to the 'hybrid model' concept.

In this way, a hybrid model is interesting from several points of view regarding the original solutions of:

- The analytical components which may be included in a project, section B.1.4;
- The numerical methods used to develop numerical models, section B.1.5;
- The experimental mechanics expertise needed in a project, section B.1.6;
- Some projects presented as examples regarding the high complexity, therefore being designated as 'hybrid models', section B.1.7;
- The software instruments used to solve the analytical, numerical and experimental problems, section B.1.8;
- The software instruments used to integrate the information resulted from the distinct studies in an meta level of understanding of the phenomena under investigations, section B.1.8.

An initial question was to comprehend what scientists understand by 'hybrid model' and what is the role of the set of concepts presented in this thesis in order to define a 'hybrid model', as it results from the experience acquired over the years. However, the definition of a 'hybrid model' should be vague because, it has the attributes of the 'concept of truth', as professor Liviu Mitrănescu taught us during the philosophy classes in 1983-1984:

- Subjective, because it is the result of a group having particular experiences and perceptions;
- Relative, because it does not cover all the aspects of the matter in question;
- Objective, because it expresses aspects, facts and solutions of real problems.

The various aspects related to the 'hybrid model' designation are presented in section B.1.2.

After we identified the basic aspects of a hybrid model, it is interesting to have an overview regarding its components, classified by the use of several criteria. The first remark is about the nature of the components which may be theoretical (analytical or numerical) or experimental. The second criterion regards the practical problems which must be solved in a 'hybrid model', being presented a long list of components, all of them being detailed in the next sections. Last but not least, according to the theoretical background criterion used to conceive and develop 'hybrid model' components, there is presented a list with some academic disciplines. There is also presented the idea that there are no 'pure' models included in a unique category, and the method to conceive hybrid models is to create a flowchart whose elements are studies with inputs, outputs, links between them, loops and criteria to stop the research, similar to the methods used in the Unified Modeling Language, aka UML[1].

The analytical components are presented in B.1.4. To be understood in a better way the aspects included in this section, a simple to complex presentation was used. Many figures were added in order to support the technical aspects. The original implementations which support the theoretical aspects are presented in B.1.8 in order to have an overview regarding the original software instruments developed over the time. The first aspect presented in this section regards the calculus domain definition, which is of highest importance for practical reasons. Along time I developed a Boolean algebra based concept used to define domains. The Boolean algebra operates with 'simple' shapes, in this class being included all the entities for which there are direct methods to compute their defining parameters, which in Strength of Materials are the geometrical characteristics. A general definition of such entity relies on the spline approximation of its boundaries, in this way being possible to virtually define any domain. Original mathematical calculus solutions were deduced, implemented and tested. Other general definition is based on linear approximation of the boundary, the entire domain being divided in polygons. The calculus relations were implemented for various shapes of the cross sections in order to study the accuracy of the method and to draw general conclusions regarding the best

[1] https://ro.wikipedia.org/wiki/Unified_Modeling_Language, accessed on August 18, 2018.

practices which lead to precise results. Starting from the domains created using a Boolean algebra, I also imagined a method for the automatic calculus of the normal stresses and shear stresses produced by the bending of beams. First results of my implementations were presented in 1998, long before these ideas could be found in the commercial software based on the finite element method. Even today, the algorithm used to select the most relevant points of the stresses offers better results than the previously mentioned commercial applications. However, from a theoretical, i.e. mathematical point of view, this Boolean algebra is general. It should be also conceived the algorithmic support needed for the practical use of the general definitions. Therefore, aspects regarding the algorithmic definitions are also included in this section, in this way being defined the grounds for the software development which is presented in B.1.8. In order to present other analytical solutions, it was approached the complex analytical model of a ship hull used to solve general ship strength problems. The complex cross sections' discretization and the automatic curves' discretization from the 'body line on frame' drawings in order to compute the buoyancy forces are some of the problems related to the model of the loads which are presented in this section. All the implementations of the analytical solutions may be used as 'building blocks' for the development of a hybrid model.

The numerical components of a hybrid model are also of theoretical nature and the original solutions are presented in section B.1.5. I started the studies with the general numerical methods and I extensively tested them in the implementations of my colleagues' research projects. Being matrix-related solutions, I conceived and developed a software project which is processing the matrices as random access files of any size. This original library was also used to develop applications based on the finite element method to solve structural problems and on the finite difference method to solve heat transfer and fluid dynamics problems. Details of the software project are presented in B.1.8.2. The mathematical background of the finite difference method applied in heat transfer problems is also presented in this section. More ideas regarding the original input data generators for the finite element applications and the original methods to import data in commercial software applications are presented in B.1.8.

Along time I considered the experimental studies to be of highest importance, therefore I participated 'hands-on' in several experimental projects. It resulted an important experience regarding the ideas and methods to conceive, develop and run an experiment, aspects which are included in section B.1.6. A problem to be solved in the experimental data reduction is to create a data subset which includes the most relevant experimentally acquired data. The criteria used to create the subsets, the implementations and some of the results are also presented in this section. Other original contribution consists of a method to automatically determine the field of isostatics starting from the pattern of isoclines in photoelasticimetry. This method uses the spline approximation of the curves, in this section being presented the theory, the implementation and the results of the study.

Section B.1.7 presents two examples of hybrid models. This concept was crystallized after 2007 when I completed the second PhD and in this section are also presented all the studies which support the concept. The first study regards the state of stresses in the block of cylinders of an internal combustion engine. Some of the experimental data is used to calibrate the model and other experimental data is used to evaluate the accuracy of the finite elements model. Once the accuracy is reached, the model is used to solve other problems, such as: weight minimization, engine installed on deflected supports and cylinder block manufactured from other material. The second study regards a half bridge of a sedimentation tank from a wastewater treatment plant. Several models were created, a 'common data' concept was defined and used to automatically generate the input data for all the theoretical models. Experiments were run using an original instrument conceived by me, i.e. a hydraulic jack fitted with a manometer, in this way being used as a force transducer. Other experimental methods were also considered. The study is a part of a PhD thesis research and I repressed the presentation of too many details before the public defense of the thesis. However, several results of the studies were presented in several WoS indexed papers.

All the aspects presented in the previous sections may be considered theories if the according solutions were not implemented. Section B.1.8.2 presents some of the software projects developed in the computational mechanics field. Previously there were mentioned the projects regarding the automatic input data generators (section B.1.8.1) and about the matrices processed as random access files (section B.1.8.2). Regarding the 'matrix' files, there were also conceived:

- Interfaces between an ASCII matrix file and various programming languages, in this way being possible to transfer information between the applications developed in distinct programming languages, in the framework of a hybrid model. In appendix C2 is presented an original software developed in AutoLISP which connects the matrix-files with the AutoCAD environment. Because AutoLISP has implemented only the sequential access files, not random/direct access files, my solution uses an external program which is run from the AutoLISP application. According to the configuration file of the external program, file created by the AutoLISP program, the external application reads from a matrix file a given element, i.e. line/record, and writes its fields in an ASCII file which is read by the AutoLISP application.
- There are solutions for the access time minimization, either by the use of a RAM drive, or by the use of the dynamically memory allocation, i.e. one-dimension array of doubly linked lists. A generalization of the doubly linked lists is also presented, the new solution being able to include distinct, various data types or data structures.
- A list of original software applications which use the matrix-files is also presented.

A solution to interface the distinct studies of a hybrid model is very important and it is presented in section B.1.8.3. It is based on CSV files, the according 'header' files being developed in C++, for various contents of the input file: numbers, strings and others. All the C++ programs to be conceived may use these 'headers' in order to access CSV input files. A similar solution was developed in OCTAVE. Similarly, for Femap/Nastran I developed an application using Visual Basic which reads a CSV file and outputs a 'Variant' data type which is used as an array of values. This array is further on used to create the sub-models of the finite element model: geometry or discretization, loads and constraints. In this way the CSV files may be used by all the components of a hybrid model.

Arbitrary precision computing became a concern when the mathematical 'pure' solutions led to overflow errors. By the use of the appropriate extended precision, this problem was overpassed and now I have an instrument to compute the summations of the expansion in series, mathematical method often used in engineering. The details are presented in section B.1.8.4.

Hybrid models cannot be conceived without the appropriate original software components, the conclusions regarding the appropriate ideas, methods and environment to develop such instruments being presented in B.1.8.5.

There are certain moments in the data processing stages when decisions must be made. The analyst cannot suspend the execution of a software in order to modify the direction in which the numerical solution is advancing. However, an analyst must consider all the criteria and the ranges of values of the approximated solutions in order to define a decisional problem. A method to make objective decisions is presented in section B.1.8.6, where some mechanical engineering case studies are also presented.

In the development of a hybrid model's software instruments, the visualizations are important because the eye is synthesizing the results graphically expressed in a more effective way than by reading a massive set of numerical information. It results that an analyst must identify the methods and the instruments to be used to visualize the data, which are briefly presented in section B.1.8.7.

There are certain cases when the rapid integration of the data or the quick development of original applications is a paramount demand. In these cases, an intelligent solution is to use metaprogramming principles. In B.1.8.8 are given some examples regarding some original programs conceived by me which are automatically generating programs. In this way, the original spline approximation processor developed in OCTAVE creates computer codes in several programming languages which may be immediately integrated in upper level applications. Other original solutions are developed in C++ and they are expressed as ‘header’ files, therefore they may be used by other C++ applications. In Appendix C1 are presented some of the automatically generated programs.

The theoretical analytical studies regarding the ship strength presented in section B.1.4.2 are continued by the software solutions presented in B.1.8.9. In the first part of the section are presented: the principles to be considered when a new problem must be solved (expressed as a flowchart), the universal problem solver algorithm conceived by Herbert Alexander Simon and an interesting algorithm based on the idea to minimize the search space of the candidate solutions. The implementation of this idea for the ship equilibrium problem leads to a volume of iterations of 2.48834E-07% of the number of iterations resulted from the Greedy algorithm for the same accuracy of the solutions. Finally, it is presented the MIPVes application dedicated to the representation of the free body diagrams and of the deflected shape of the structure for an analytic model of a ship hull. The facilities of the application are briefly explained.

The academic activities are presented in B.1.9. The officially recognized course in educational problems, a list of valuable graduates who confirmed their value and the Bologna Professor recognition are the first ideas presented in this section. It follows the educational methods I use in order to increase the motivation of the students: bonus for attendance, bonus for intelligent answers and comments, multimedia teaching aids to be commented during the classes, partial exams. Integration of the Strength of Materials discipline in the context of the curricula, diagrams with the set of main topics and which are presented at the beginning of each course, the original feedback form to be completed in the final weeks are also mentioned. Two examples regarding the visual teaching aids are also presented.

Section B.2.1 includes directions of development in research, being identified four main directions.

A first group of ideas is dedicated to the pattern recognition across domains and the methods to apply new exotic algorithms from IT, for instance meta-heuristic algorithms, in order to solve problems in other fields of science, such as internal combustion engines. One can notice a wide field of new research topics which may use the software instruments already developed by me.

Conceiving new calculus methods in mechanical engineering based on original mathematical approaches is the second group of ideas. There is a list of problems which may be modeled as a rational continuation of the problems solved so far. The software solutions may be used as 'building blocks' in other upper level projects such as automatic dimensioning or hybrid models.

Conceiving new computing and visualization methods in mechanical engineering based on the most recent IT progresses is the third direction.

New ideas for the flexible development of the software instruments may be found in the ‘design pattern’ technical literature.

Parallel computing is a method to create fast solvers which may be used to conceive new mathematical solutions and new algorithms. In this regard, Open MPI and CUDA may provide the technical support for such developments.

Arbitrary precision computing topic is important, in this direction being necessary trigonometric functions of customizable precision which may be used in trigonometrical series. I remind that one of the solutions to avoid ‘overflow’ errors is the arbitrary precision computing.

Regarding the development of the graphical interpreters for scientific visualizations, several ideas may be used: OpenGL API for customized graphics, the CGAL library for geometry algorithms and ParaView for high level solutions. For the partitioning of the finite element meshes and of the graphs there may be used METIS, which has both, standalone programs and an application programming interface.

A component of the software instruments' development environment is OCTAVE, being necessary to embed OCTAVE libraries in C++ applications. In this way there may be used advanced numerical methods' solvers in the C++ instruments of the hybrid models.

Creation of laboratory works which allow the remote access may lead to the creation of an e-Labs' network to be used in time sharing by various universities and research groups. This is another idea which may be developed in the experimental studies' direction.

A direction of academic development, section B.2.2, is to increase our students' emotional intelligence together with their technical knowledge and skills. In this way the students should be aware that "*IQ gets you hired, but EQ gets you promoted!*". Students must be also encouraged to connect the influences of various types in order to understand a phenomenon: high/low temperatures, corrosion, special materials and others. Collecting new images and videos to be included in the library of multimedia teaching aids is other direction.

The abstract is a brief presentation of the thesis, which is a concise report of my activity over more than three decades. To conclude, the models and mentors I had during the undergraduate and especially along the doctoral studies helped me over the years to find the best solutions in times of questions, of various questions. I understood that the hard work, the patience, the determination and the willingness to build a hierarchy of true values, as my professors are, will always be rewarding. I consider this thesis as a sign of gratitude to them and a promise to the next generations.