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Experiences in Teaching Multibody Dynamics

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Abstract. The use of multibody dynamics software in industrial firms is steadily increasing. Engineering curricula often do not include mandatory courses where multibody dynamics is taught. This paper, after a discussion on some teaching needs in this specific cultural area, reports on the experiences matured by the authors when introducing these courses at two Italian universities.

Keywords: Engineering education, multibody dynamics, teaching methodologies

1. Introduction

The Italian engineering schools were recently required by law to change their traditional five years curricula. Under the current rules a student, after three years, may obtain a *laurea* degree in engineering . Then, he/she can pursue further studies and obtain, after two years, the *laurea specialistica* degree. One year master courses are optionally organized by the universities which offer also a three year doctoral programs.

The change imposed a radical revision of the program of studies. It should be acknowledged that many engineering teachers are complaining about the influence that this reform of studies is having on the level of technical skills of our engineering graduates. However, we shall not discuss about such a topic, but the mention was necessary in order to introduce the cultural environnement in which the reported experiences were developed.

The content of textbooks traditionally used by mechanical engineering students for learning machine dynamics (e.g. [1, 2]) focus on Newton-Euler approach and on simple planar inverse dynamics models. Forward dynamics is often limited to the classical one or two degrees-of-freedom linear models used in vibrations. When present, the computer coding of the problem is based on *ad hoc* models whose equations are deduced by hand.

Since the number of credits for mechanics courses is somewhat limited, this approach is currently continued. Thus, the teachers are forced to limit their lectures to the basics of machinery dynamics instead of extending them by introducing multibody dynamics techniques. From colloquia with collegues it seems that the above situation is not uncommon at many european universities.

The widespread diffusion of multibody dynamics software calls for attention. In fact, a significant portion of european mechanical engineering graduates are potential users of such a software without having a minimal knowledge of its theoretical bases.

Moreover, many current users, although familiar with the graphic interface, lack the basic understanding of the theory behind the code. Unfortunately, software packages without a detailed theoretical manual are not rare and the courses organized by the companies, due also to time constraints, usually focus on the working features of the code and not on its theory.

In a recent past, multibody dynamics was more a research topic rather than an established subject for mandatory university courses. Although many distinguished researchers in the field published textbooks describing the details of their methods, few universities offered courses in modern multibody dynamics. With the advent of software packages based on multibody dynamics techniques, the need is arising for the introduction of courses where the derivation of the equations of motion is presented in a computer oriented manner together with time integration algorithms.

The current situation has similarities with the pre-finite elements era. In the sixties few university curricula included a course in finite elements. Nowdays the situation is radically changed. There is not any university offering a degree in mechanical or civil engineering without a mandatory course in finite elements.

The correct interpretation of the results obtained from a software requires not only the knowledge of the components under analysis but also the understanding of the theoretical bases used for its developement. This is a widely accepted opinion in engineering.

Considered the current status of mechanical engineering curricula, many users of multibody dynamics software may not be fully aware of the limits of their models. The potential danger of the above described situation requires some action from the multibody dynamics research community.

This action can take different forms according to the target of the instruction:

- students with no background in multibody dynamics and little or no experience of CAE software;
- engineers already using CAE software;

For this last cathegory of individuals, the continuing education programs offered by the universities or private companies should foresee lectures on theory and practice of multibody dynamics. The practice should involve also the modeling of real mechanical systems. Noteworthy attempts in this direction can be recorded.

Serious problems may arise by the use of simulation software, such as multibody dynamics codes, by CAD practitioners. Although extensive training is required to be expert in using a computer to create solid models, this does not makes the person an engineer [26]. Whoever is setting up the model must understand what kind of assumptions he/she is making.

The mechanical engineering community benefit from self-study systems and use of world wide web as a teaching tools [3]. Little is known on the effectiveness of such systems for learning multibody dynamics.

2. Preparation of the Multibody Dynamics Course

According to the experience of the authors, an instructor willing to organize a course on multibody dynamics theory will face different choices. The following items summarizes some of the main problems identified.

- **Prerequisites**
  Multibody dynamics is an advanced topics. Students should have a background in physics, numerical analysis and machinery dynamics. Computer programming skills are also required.
- **Kinematic formulation and dynamic principles**
  In multibody dynamics there is a wide choice of generalized coordinates (e.g. Euler angles, Cardan angles, Euler parameters, Denavit-Hartenberg, dual numbers,...) and methodologies for the systematic description of kinematic constraints (*e.g.* method of constraints, loop-closure equations,...) in mechanical systems.
  Moreover, the equation of dynamics may be deduced from different approaches (Newton-Euler, Lagrange, Gibbs-Appell, Jourdain, Gauss, ...). Which kinematic formulation and dynamic principle is the most effective for teaching? Although this is a key question a definite answer cannot be given, and the final choice depends on the instructor's personal judgement and preferences. However, the teaching of dynamic formulations adopted in commercial software is recommended at least in introductory courses. The student will have a better understanding of the theoretical bases and limitations of the software.
  In the bibliography a list [4–24] of textbooks dedicated to multibody dynamics is included. Likely the list is far to be exhaustive. However, it is a good starting point.
- **Course length**
  How many hours are required to teach basic multibody dynamics course for graduate students? According to the authors' experience, 45 hours distributed in 15 lectures (2 lectures each week) should be enough. For experienced engineers, three days intensive course seems a reasonable length. In this case the instructor concentrates mostly on theory and numerical methods and less on programming.
- **Preparation of material to be distributed**
  Homework assignements and computer programming tasks should be clearly stated in handouts. Reference to the equations in textbooks will help the students. The reference to papers taken from technical literature may be useful when dealing with advanced topics.

- **Computer programming**
  The students must have normal skills of computer programming in a higher level language of their choice.
  They are required to develop software with the following modules: data input and output, automatic build up of equations and numerical solution. Through the computer programming of a multibody dynamics methodology the students usually reach a deep understanding of the subject. For this reason computer programming is strongly recommended in basic multibody dynamics classes. The instructor can make available pieces of code that the students may use during the developement of their own software. This will help the students not to get lost in coding the all software, but to concentrate on the overall structure of the program. Guidelines on the input/output of data and on the overall structure of the code should also be discussed by the instructor.
  The students should also be encouraged to use professionally tailored linear algebra and numerical integration subroutines available in packages such as IMSL, ODEPACK, LAPACK, MATLAB, MAPLE, etc.
- **Use of commercial multibody dynamics software**
  At university level, how much emphasis should be given to the teaching of commercial software? Also in this case there are different answers. Some teachers argue that the students should be educated to a correct use of commercial software. Since user's interface and capabilities of a software change almost every year, other teachers, during instruction, put more emphasis on the theoretical part of the methodology rather than on the practical use of the software.
  We believe that both aspects are relevant. The current trend is for the development of software with friendly user's interface. Thus an engineer can make himself familiar very quickly with the solid modeling and multibody dynamics software. Many companies offer specialized training on the specific software being used at their site. This training usually focus much more on the practical use of the software and less on its theoretical bases or limitations. The training offered at university level should involve a type of knowledge valid in the long term. Students are usually attracted by the use of simulation tools and less by the theory. Thus a teacher must search for a compromise between the instruction of the use of commercial software and the teaching of multibody dynamics theory. However, the correct use of the multibody dynamics software requires also the physical understanding of relationship between system response and components parameters. This type of knowledge, achieved through education and experience, is usually based on *ad hoc* simplified analytical models.

3. The Authors' Experience

Two of the authors (E.P. and R.S.) recently introduced a course on multibody dynamics in the engineering curricula at their universities. The courses are mandatory for mechanical and automatic control engineering students. This section describes some of the choices and may offer guidelines for similar initiatives.

3.1. COURSE SYLLABUS

The method of constraints for planar kinematic analysis. Revolute, prismatic, gear and cam pairs are considered together with other 2 degrees-of-freedom types of constraints. The automatic assembly of the systems of equations for position, velocity and acceleration analysis. Iterative solution of systems of non linear equations. Geometry of masses. The principle of virtual work and Lagrange's equations. Dynamics of planar systems. Systematic computation and assembly of mass matrix. Computation of planar generalized forces for external forces and for actuator-spring-damper element. Simple applications of inverse and forward dynamic analysis. Numerical integration of first-order initial-value problems. The method of Baumgarte for the solution of mixed differential-algebraic equations of motion. The use of coordinates partitioning, QR and SVD decomposition for the orthogonalization of constraints. Kinematics of rigid bodies in space. Reference frames for the location of a body in space. Euler angles and Euler parameters. The formula of Rodrigues. Screw motion in space. Velocity, acceleration and angular velocity. Relationship between the angular velocity vector and the time derivatives of Euler parameters. Kinematic analysis of spatial systems. Basic kinematic constraints. Joint definition frames. The constraints required for the description in space of common kinematic pairs (revolute, prismatic, cylindrical, spherical). Equations of motion of constrained spatial systems. Computation of spatial generalized forces for external forces and for actuator-spring-damper element. Computation of reaction forces from Lagrange's multipliers.

Considered the introductory level of the course and the lack of funds for the renting of licenses, hands-on practice with multibody dynamics commercial software was not included in the course. Due to time constraints, flexible multibody topics are omitted.

3.2. HOMEWORK AND COMPUTER ASSIGNEMENTS

The homeworks requested are the development of computer codes for:

– the kinematic analysis of planar mechanisms with lower pairs
– the forward dynamic analysis of planar mechanisms with lower pairs, spring-damper-actuator elements, external forces;
– dynamic analysis of a 3D mechanical system composed of two rigid bodies with revolute, prismatic or spherical pairs.

The students were also requested to document their code to the best of their capabilities.

3.3. COURSE GRADING

The overall grading is based for 50% on the quality of the computer assignements handed during the course, 25% from written test and a 25% on a brief oral exam on different parts of the theory.

3.4. RESPONSE AND COMMENTS FROM THE STUDENTS

The students seems enjoying the study of multibody dynamics theory. What they like most is the sistematicity of the approach. The computer oriented modeling of mechanical systems makes them more confident about the formal correctness of the governing equations deduced. Most of the complaints arise from the limited time allowed for computer homework. In fact, they claim that the theory is easy to learn and understand, but debugging of the software takes most of their time. They find also useful to do experiences with specialized software for linear algebra and numerical integration of differential equations. The software tools chosen for computer programming were Fortran90, C++, Matlab, Maple and Mathematica. The course, started in 2000, is attended by about fifty students each year.

4. Conclusions

The training in theory of multibody dynamics of mechanical engineering students has been discussed. On the basis of their experience, the authors recommend that multibody dynamics courses should be preferentially offered during or after the third year of an engineering curriculum. This will ensure a minimum of background. The question on the *most* effective syllabus is still open. It would be interesting to compare the proficiency in modeling mechanical systems of the students exposed to different multibody dynamics methodologies.

The inclusion of more advanced multibody dynamics topics in mechanical engineering curricula seems is not widespread in European universities. For instance flexible multibody dynamics is still perceived like a research topic rather than an established discipline. The scarsity of textbooks, usually very expensive, and of ready-to-use didactic material does not help the diffusion of courses. Due to the lack of funds, the renting of commercial software licenses is also a problem. However, from the didactic point of view, the development of open source multibody dynamics software, made freely available to teachers and students or under a nominal fee, would greatly help the spread of the culture of multibody dynamic in the engineering curricula. Centralized web resources, where students and educators may find links to reports, tutorials, software on the different branches of multibody dynamics are also useful for the above purposes.

The efforts in the developement of didactic tools and teaching methodologies in the field of multibody dynamics are worthwhile. Beside the already mentioned advantages of informed software users, the research in multibody dynamics will surely benefit of a large base of graduate students familiar with the basic techniques.

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