HERE WILL BE LOGO

Further results on Modeling, Integrated Design and Simulation of a Mechatronic System with FPGA

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Summary:

The basic idea of modeling, integrated design and simulation of mechatronic product is to combine benefits of the mechanical multibody system model with the features of advanced drive and control.
The starting point for multiphysics modeling and simulation is multibody system dynamics with the practical case - washing machine. The motion equations are obtained using modified symbolic Lagrange equations in a covariant way, applying the Rodrigues method. In this paper it will be presented a novel means of designing a simple and effective torque control for PMSM based on the Field Programmable Gate Array (FPGA) technology. Finally, the effectiveness of both suggested approaches is is demonstrated on mechatronic system simulation (e.g. co-simulation approach) on planar washing machine model. There are given also practical hints for promising hardware-in-loop simulation for experimental evaluation.

Key words: *mechatronics, rapid-prototyping, multi-body dynamics, FPGA, drive control*

INTRODUCTION

The design of mechatronic product is very complex and comprehensive task, since there are combined solutions and technologies from intersecting fields of mechanical, electrical, control and software engineering. Although, there are present some industrial guidelines as design methodology for mechatronic systems – e.g. V-model, where the product designer decompose the product into the hierarchical sequence (modules). These modules are then treated as independent items with own modeling

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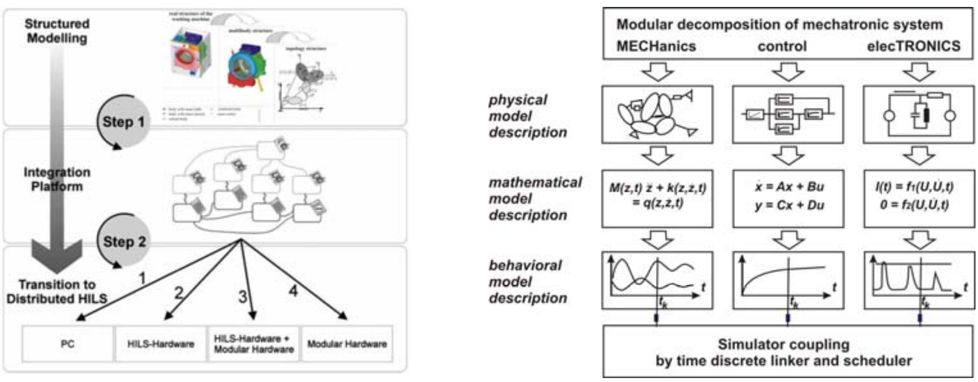
and simulation procedure. To implement mechatronic product development process, the product designer often faces numerous challenges – e.g. lack of cross-functional knowledge, difficulty implementing an integrated product development solution for all disciplines involved in mechatronics product development and inability to understand the impact a design change will have across disciplines. Additional complexity is the expectation for real-time coordinated response from the mechatronic product (e.g. robot) and its subsystems. The proper answer for the parallel and distributed process control as reliable (industrial) solution is enabled by the FPGA (Field-programmable Gate Array) technology. In this article, we are going to present the case of the mechatronic system – multibody system dynamics and the drive, where the simulation is considering mechatronic system's dynamic with various drive properties.

1. The mechatronics system and modular approach

The design of mechatronic systems could be roughly distinguished in four stages: modeling, analysis, controller synthesis, and hardware-in-the-loop-simulation (HILS) to test the system in the lab (**Figure 1a**) .



a.) *Mechatronic system design* **b.)** *Modular modeling and simulation*

Figure 1: *Mechatronic system – modular decomposition and modeling description*

The model description of each mechatronic module could be done also independantly as physical, mathematical and behavioral description (**Figure 1b**). On the market could be found some very capable software tools, which enables coupling the simulation on different physical domains (e.g. LMS Virtual.Lab, MD Adams, PSpice).

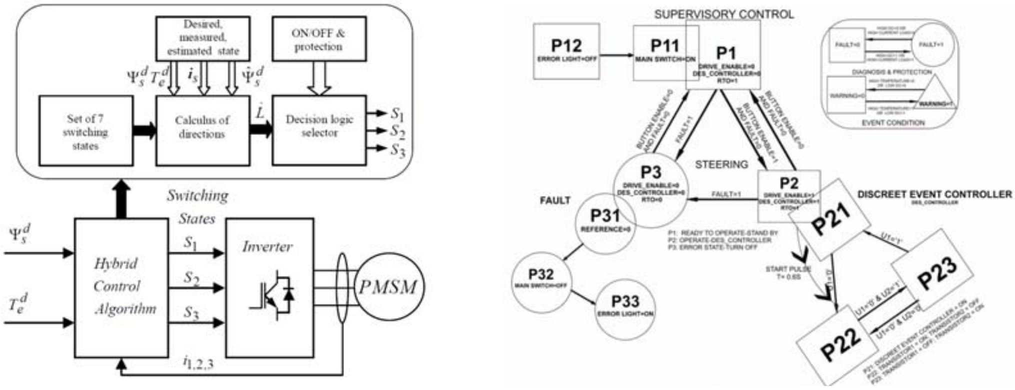
1.1 The multibody system dynamics and modelling

Main goal by analysis of multibody system dynamics or dynamics of mechanical systems is therefore to develop such formalism procedure (modeling, formulation, numerical) that automatically generate the equations of motion for multibody systems.
The multibody dynamic system (mechanical part) could be presented on many different ways – e.g. tree structure. Modeling mechanical systems is mostly done by numerical methods, but the application of symbolic equations provide numerous advantages. One of them is providing more efficient models for parametric evaluation as well as for real time-simulation and control.These theoretical advantages, this method could be

useful for certain practical engineering tasks – e.g. easily obtaining and modeling 3D models of MBSs.

1.2 The multibody system dynamics and modelling

The household appliances (washing machines) are multibody dynamic systems with changing loads, which require advanced control techniques such as use of notch filters to avoid exciting the system at resonant frequencies, or gain scheduling to adjust for changing load inertia. This also requires customizing the torque loop in addition to position and velocity, while others may require custom drive electronics including custom commutation algorithms for optimal performance. An optimal washing process has to take into the account key factors (or Sinner's factors) - temperature (heating), chemical action (detergent, bleach, water), mechanical action (spin rotations by the drum of washing machine), and time (duration of washing cycle). All that requires multiple input and output (control) signals for multiple drives and sensors , which have to be managed by the control unit in very short response time in very common way with DSP (Digital Signal Processing)/MCU (Microprocessor Control Unit) or advanced way - example the Permanent Magnet Synchronous Motor (PMSM) and FPGA (Field Programmable Gate Array). Very promising solution is hybrid FPGA/DSP technology, where configurable platform offers more performance and I/O adaptability, while still providing low cost for high volume production. An important advantage of using an FPGA for the controller is also that some additional functions like protections, steering, monitoring etc., can be added with no additional resources and almost no drawback in performance showing in (**Figure 2a**) - conceptual representation of a hybrid switching controller. The FPGA concurrency allows executing the logic dedicated to the proposed hybrid direct torque control (DTC) and any additional logic denoted to protections simultaneously. In fact, any algorithm can be added to control one while there are available resources. As presented on the **Figure 2a** - the decision logic selector that controls the switches, or more precisely, that generates the switching control input vector $\boldsymbol{S}$ (S_1, S_2 , S_3). Its purpose is to monitor the signals that can be measured or estimated and decide, at each instant of time, which candidate input switching vector $\boldsymbol{S}$ should be put in the feedback loop with the process. In the supervisory control, the supervisor combines continuous dynamic with discrete logic and is therefore hybrid system. Motor torque T_e is expressed as imaginary part of complex product between rotor flux and stator current. The FPGA based DTC PMSM system is meant to be operated according to certain established rules and principles, which are presented in **Figure 2b** as infinite state machine (ISM) in three domain principle. The rectangular ISM describes normal machine operation including start/shut/up/down operation, hybrid controller normal operation. The triangle ISM represents a potential risk for the PMSM with inverter if a major driving parameter drifts into it, or if a failure occurs. The circle domain is out of the limits of the safe field of variation of the parameters and system automatically switches off.



a.) *Hybrid control od AC motor* ***b.)*** *State CAD diagram*

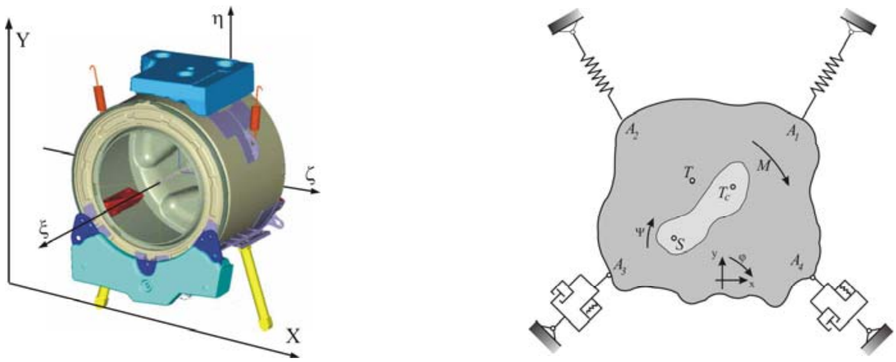
Figure 2: *FPGA Supervisory control of AC motor and state CAD diagram*

1.3. The mechatronics system modelling and FPGA

Main issue to conduct the mechatronic system modelling is to assemble the simulation model of mechatronical system as a multiphysical system - to interconnect the simulation models of particular subsystems of certain physical nature into one resulting multiphysical (multidisciplinary) modeling. There are two different approaches, co-simulation (tight and weak coupling) and uniform modelling with different formalism - equations (algebraic, differential), dynamic blocks, multipoles and bond graphs. Nevertheless, the natural basis of simulation models of mechatronic systems are the multibody models that are feedback controlled, where the mathematical models and corresponding simulation models are being developed for systems from one physical domain. After modeling, simulation and control synthesis - the designer has to proceed with the final stage, hardware in loop (HIL) simulation. Namely, without the real time simulation with actual analog and digital signals the mechatronic product could not be properly validated. In the HILS the stepwise transition from the pure model representation of the mechatronic system to actually mounted mechanical, hydraulic and electrical components takes place.

2 The mechatronics system dynamics – case study

The case study of mechatronics system dynamics is the (planar) model of washing machine, the tub assembly without the cabinet (**Figure 3a**). The 2-D multibody system model, which could be presented in classical approach (**Figure 3b**) or robotical approach , consists of two rigid bodies which are supported by cabinet of washing machine. The first rigid body, with its centre of gravity at point T, is called the basic body. Its links to the surroundings consist of a bilinear spring support, linear viscous damper and element with implemented dry friction. All of the elements of vibro-isolation are collinear with the axis of the co-ordinate system *xy*. The second rigid body, with its centre of gravity at point T_e, is called the rotor. It is driven by torque *M*(*t*) and attached to the basic body by bearings at point *S*. The model has four degrees of freedom (DOFs) where coordinates *x*, *y* and φ are needed to determine the motion of the basic body.



a.) *Tub assembly of washing machine with suspension*

b.) *Planar model - classical approach*

Figure 3: *2D model of analyzed washing machine*

The *x* and *y* describe the horizontal a vertical translation of the basic body, respectively, and φ describes its rotation. To characterize the rotation of the rotor the additional coordinate ψ is used. The φ and the ψ start at *x*-axis.

2.1 Stationary system response

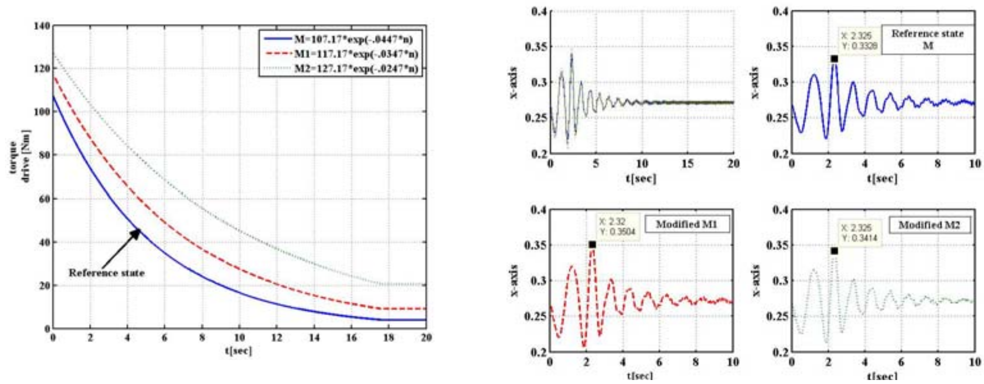
The reference state for comparison is displacement at steady rotation (ω = const), which is taken for the angular speed ω = *1000 rev/min* = 104,72 rad/s (frequency *16,67 Hz)* for given drive's torque profile (**Figure 4a**).

2.2 Drive properties change and system response

The drive properties change should be adjusted to the changeability or variableness load, which is quite common phenomenon by certain mechatronic product - e.g. washing machine, walking prosthesis. Very common DSP system with central MCU or non-FPGA solution has very limited possibility to follow up and also quick adjust the drive properties to achieve better system's stability. This issues could be tackled with the hybrid, DSP/FPGA approach and solution depends solely upon the mechatronic product. In the following diagram (**Figure 4b**) is presented system response upon the drive change in both planar axis x as well as rotational speed φ for the chosen mechatronic product – washing machine (**Figure 4a**) for 10% (**M1**) and 20% (**M2**).
On all three figures above is presented a comparison among the reference state of the drive property with the drive modification. The modification of the drive properties for 10% (**M1**) and 20% (**M2**) cause the raise of deflection for up to the 7%. Consequently the accelerations and forces cause the raise of unnecessary vibrations and noise.

3 Comments

In this paper, equations the motion of a mechanical system are written down in s.c. robotic way (applying the Rodriguez method), modified symbolic Lagrange equations in a covariant way.



a.) Drive's torque profile *b.) Drive modification - displacement in x-axis*

***Figure 4:** Steady state response - displacement in XY plane and reference drive profile*

Presented is co-simulation approach of mechatronic system with the drive modification and multibody dynamic system response, which is very good basis for further experimental evaluation (e.g. FPGA hardware-in-loop simulation).Even the slightest changes of drive properties could cause the substantial increase of system's deflection and further vibrations. This only proves the necessity of advanced control in very short response time. Main issue to conduct the mechatronic system modelling is to assemble the simulation model of mechatronic system as a multiphysical system - to interconnect the simulation models of particular subsystems of certain physical nature into one resulting multiphysical (multidisciplinary) modelling. The mechatronic (washing machine) product's control unit should act in very short (response) time. Rational and efficient application FPGA technology and related hardware-in-loop simulation (HILS) demand also efficient mechanical model - in our case modified, symbolic Lagrange's equations of motion mechanical system in covariant way or robotical (Rodriguez) approach.

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LITERATURE - only the selected

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