

Multi-body modelling of mechatronic systems with flexible and nonlinear dynamics

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Abstract

This work describes the software framework for multi-body modelling and simulation of the semicon machines developed at the ASM Center of Competency in collaboration with the Eindhoven University of Technology. Thanks to high level of automation of the model building, this framework significantly simplifies and speeds-up the modelling and analysis of the integral machine dynamics, together with control simulations. Such automation also minimizes occurrences of the modelling errors and enables even non-specialists in nonlinear and flexible systems to effectively perform machine design optimization, root-cause analysis, and troubleshooting of performance and reliability issues. The framework is demonstrated by effective modeling of a semicon bonding machine and verified by convincing matches between simulations and actual measurements.

Multi-body modeling, Flexible dynamics, Simulation

1. Introduction

Next generations of semiconductor machines require continuous improvements in performance and reliability. At the same time, firm market competition limits selling prices of these machines. To enable further performance improvements under constraints on the machine costs, more effective strategies to product development become necessary. An appealing solution is multi-domain model-based product development, which enables analysis and optimization of the integral machine electromechanical dynamics, including communication and software, right from the earliest stages of the system development [1,2].

A common characteristic of the existing mechatronics approach is the system design optimization at a limited number of the operating points (e.g. motion or temperature). To achieve high system performance, the mechatronics design exploits dominantly linear input-output behaviour of the resulting system in close neighbourhoods of these setpoints. The linear approach greatly facilitates understanding of the machine dynamics and control design for high-performance and disturbance rejection. However, semicon machines have wide operating ranges and exhibit variations in their dynamics including non-negligible nonlinear effects. Direct compensation for the changing and nonlinear machine dynamics is not common in classical mechatronics, whereas it appears inevitable for achieving advanced performance and high robustness against disturbances. Fortunately, The Netherlands has a strong academic expertise on nonlinear systems, e.g. [3,4], which can readily be combined with the existing mechatronics know-how. By theoretically sound and explicit treatment of the integral system dynamics, including structural deformations and nonlinearities, many principles of the mechatronics system design approach can still be used for advanced design of new and improvement of existing semiconductor machines.

There is a sound theoretical foundation for modeling of multibody systems that consists of connected rigid and deformable parts. The usual first-principles modeling approaches utilize either a floating frame of reference formulation [5] or the absolute nodal coordinate formulation [6]. These approaches are however not common in professional practice due to high modeling complexity and advanced modeling expertise required. Numerical modeling using a finite element method (FEM) [7] is therefore an industrial standard and a wealth of software packages exists for FEM modeling and simulation of the multibody dynamics with flexibilities.

This work describes the software framework for multi-body modelling and simulation of the semicon machines, which is being developed at the ASM Center of Competency [8] in collaboration with the Dynamics and Control Group of the Eindhoven University of Technology [9-11]. This framework utilizes affordable commercial software tools, such as Matlab/Simulink/Simscape Multibody™ [12] and Hyperworks/MotionView [13]. It enables modeling of integral machine dynamics including structural deformations, nonlinearities, coupling effects, etc. A high level of modeling automation greatly simplifies and speed-up development of the integral models. These models are applicable over wide working ranges of a machine instead of small neighborhoods of specific operating points. By application of the mechatronics design principles on the integral models, systematic design optimization and performance prediction of complex mechatronics equipment become possible. To illustrate practical benefits of this framework, we share our

experiences with multi-body modelling of a bonding semicon machine. We also demonstrate predictive quality of the resulting models by comparing simulation results with measurements obtained on a physical bonding system.

In Section 2, we set the requirements on the software framework for integral multibody modeling and select state-of-the-art software tools that fulfil these requirements. In Section 3, we describe our software framework and demonstrate it by modeling a bonding machine. Predictive quality of the developed models is illustrated in Section 4. Conclusions and outlook of further activities are given in Section 5.

2. Modeling software tools for mechatronics system development

Having in mind increasing complexity of semicon machines, such as wire- or die-bonders, it is practical to consider commercially available high-end software packages for FEM multibody modeling and simulation. To make the optimal choice on the commercial tools to be incorporated into the software framework for the mechatronics system development, we set several criteria:

- capability to model and simulate complex multibody systems with flexible dynamics,
- high level of modeling automation, including ability to generate multi-body dynamical models based on imported CAD geometries,
- ability to perform control simulations using either of the following three methods:
 1. integration of the model of the machine dynamics and its simulation within the software environment dedicated to control engineering, such as Matlab/Simulink;
 2. modeling and simulation of the controllers in the same software environment as used for multibody modeling;
 3. co-simulation of the software for multibody modeling with the control software,
- ability to include dynamical disturbance effects, such as external vibrations and sensor noise, and discretization effects in time and magnitude,
- ability to model various types of passive damping, such as proportional/modal damping, general viscous damping, viscoelastic damping, and frictional damping,
- ability to model and simulate forces related to the contacts between components of the multibody system, such as friction, and collision forces,
- availability of different analysis methods, such as structural dynamics analysis, vibrational, and stress/strain, etc.,
- ease of use including the features that simplify the pre- and post-processing of the models for the sake of managing their topologies, complexity, and configuring their parameters.

Several commercial tools for FEM modeling and simulation of flexible multibody dynamics have been studied and evaluated in terms of the given requirements. In fact, the tools that are commonly used in the Dutch high-tech sector are primarily considered, since for these there exists sufficient industrial experience with well-established customer support and pricing conditions. Examples of these tools are Adams, Ansys, MotionView, Comsol, etc. Each of these tools enables simulation of the flexible dynamical systems over time-varying operational ranges and not only at specific working points, which allows analysis of time-varying and position-dependent dynamics.

From our evaluation, it turns out that a multibody modeling tool MotionView from the Hyperworks suite of Altair satisfies all the considered criteria and enables all three methods for performing the control simulations. In addition to these capabilities, MotionView enables multi-physics simulations (e.g. thermal, fluids, acoustics, magnetism), different optimization functionalities (e.g. topology optimization, shape optimization, multi-disciplinary optimizations), and advanced structural analysis features (e.g. incorporating nonlinear material properties and nonlinear deformation effects). These are the reasons why we have decided to incorporate the MotionView into the framework for integral modeling and simulation of the semicon machines.

In the semicon industry, many mechatronics engineers make use of different Matlab tools, such as Simulink, for product development and analysis. Convenience and effectiveness of these tools is proven in practice. Multibody modeling is particularly facilitated thanks to the dedicated toolbox – Simscape Multibody™. This toolbox offers a library of different modeling blocks representing bodies, joints, constraints, force elements, and sensors. Since recently, the multibody model of a system can automatically be generated based on CAD models of mechanical assemblies. That greatly simplifies the modeling process and allows mechanical and mechatronics engineers to perform fast and effective evaluations of their designs in terms of dynamical characteristics and control performance. A practical limitation of Simscape Multibody™ is lack of direct tools for modeling structurally deformable parts. Also, FEM models cannot directly be imported and incorporated. However, advantages of Matlab and its tools for modeling, analysis and design, together with their acceptance by broad engineering community, are the drivers to investigate merits of Matlab/Simulink/Simscape Multibody for modeling and simulation of the semicon machines. That is why in the next section we explain the process of automated multi-body modeling and illustrate it on an example of a semicon machine. We also suggest a method to incorporate a FEM model of a structurally deformable part.

3. Multibody modeling of a semicon machine

Let us consider a bonding machine with a CAD design shown in Figure 1. A multibody model of a such a machine can automatically be generated in Matlab/Simulink/Simscape Multibody™. The resulting model connects discrete mechanical entities, such as rigid-bodies and joints that represent degrees of freedom (dof's) and lumped flexibilities. Since dynamics of structurally deformable parts cannot directly be modelled, these must be manually incorporated. The automated lumped element modeling procedure is explained in Section 3.1 together with a way to include a FEM representation of distributed flexibility. In Section 3.2, we show that a multibody model of the same semicon machines, which consists of connected rigid-bodies, nominal dof's, lumped flexibilities, and structurally deformable parts, can directly be generated in Hyperworks/MotionView.

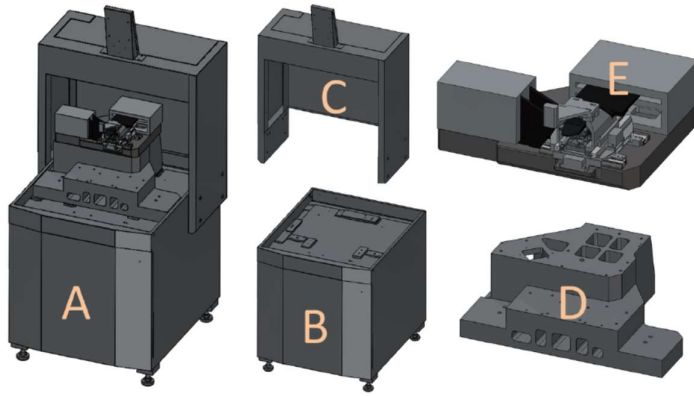


Figure 1. CAD layout of a semicon machine: A) assembled system, B) base, C) casing, D) casting base, and E) XYZ-motion stage.

3.1. Automated lumped-element modeling

Generation of a multibody model of the semicon machine in Matlab/Simulink/Simscape Multibody™ is summarized by the flowchart shown in Figure 2a [9]. To enable automated model generation, the CAD model of the machine needs to be opened either in SolidWorks [14] or Onshape [15] CAD software. The former one is a well-known standalone software package and the latter one is the cloud-based CAD tool. If the original CAD files are not fully compatible with these tools, one may need to make them compatible by reassembling the parts (constraints settings) and reassign their material properties. Both SolidWorks and Onshape enable exporting of geometric and inertial properties of the CAD assemblies together with the specified motion constraints. That is done via an .xml file. Also, STEP files are exported to visualize the CAD assemblies. The exported files can directly be imported in Matlab, which automatically creates the corresponding multibody model in the Simscape Multibody™. In the generated model, the motion constraints define locations of the joints that represent the nominal dof's of machine, such as X-, Y-, and Z-axis of the motion stage shown in Figure 1. The lumped flexibilities are then modelled by adding additional joints at locations of these flexibilities and specifying their stiffness and damping parameters. Thanks to compatibility of the Simscape Multibody™ and Simulink, the multibody model can be extended by standard implementations of controllers, sensors, friction and disturbance effects, delays and discretization effects, setpoint generators, etc.

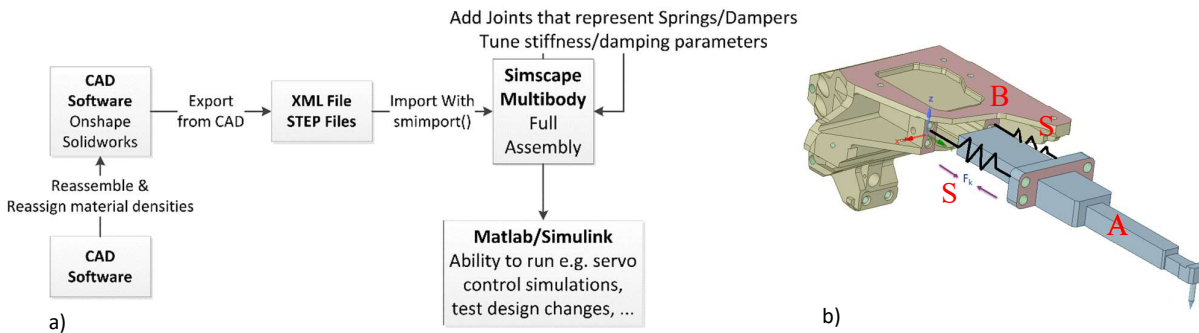


Figure 2. a) Flowchart of the procedure for automated building a Simscape Multibody™ model starting from CAD files and b) Interfacing a FEM model (A) in the state-space form with the lumped element model (B) via spring elements (S).

Incorporating a model of a structurally deformable part into the Matlab/Simulink/Simscape Multibody™ environment is not trivial. A practical solution is worked out in [9] and it consists of the following steps: 1) create a FEM model of a deformable part using appropriate software, 2) represent the FEM model in the state-space form which can be implemented in Simulink, 3) use springs of high stiffness to model contact forces at the interface points between the deformable part and its neighboring body; these springs create forces that simultaneously act at the interface points from the lumped element model and serve as inputs to the state-space representation of the deformable part. This method is illustrated in Figure 2b where two springs interface a slender deformable part of the bonding tool with the rigid central body. Besides knowledge of multiple software environments, this method demands expertise in multibody modeling for proper interfacing the state-space and lumped element models. The interfacing is even more complex if multiple state-space models need to be integrated. Consequently, if structurally deformable parts need to be incorporated into the multibody simulation, it is more convenient to use dedicated software tools that directly support FEM modeling.

3.2. Multibody modeling using the dedicated FEM modeling software

Multibody modeling in Hyperworks/MotionView is performed in a graphical environment which allows both manual definition of the model entities as well as importing of CAD assemblies [11]. In both cases, the user must define material properties of the individual bodies and their interconnections. The interconnections can represent nominal dof's of the mechanical structure, rigid or flexible interfaces between the bodies. FEM models can directly be imported and assigned to the deformable bodies. To enable control simulations, three options are available: 1) export the multibody model in the state-space format and implement it in a software for control design and simulation, such as Simulink; the key limitation of this method is a local nature of the state-space model, since it represents a linearization of the multibody dynamics at a given operating point; 2) the complete multibody model can

be run in Activate, which is a Hyperworks tool for control simulations; 3) the complete multibody model runs in co-simulation with controllers implemented in Matlab/Simulink. Methods 2 and 3 enable control simulations over complete working ranges and thus are more generic than method 1. As a case-study, the semicon machine shown in Figure 1 is modelled Hyperworks/MotionView and both methods 2 and 3 for control simulations are tested. As examples, in Figures 3a and 3b we show MotionView visualizations of the semicon machine and of its isolated bonding tool, respectively. The bonding tool features exaggerated deformation in its slender part, which demonstrates simulation of structural deformation.

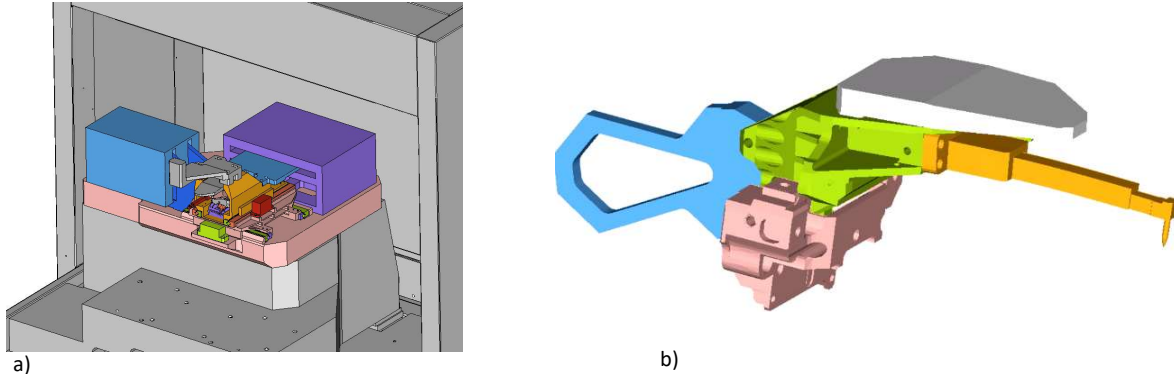


Figure 3. Snapshots of the semicon machine modelled in Hyperworks/MotionView: a) part of the complete machine and b) isolated bonding tool.

4. Illustrations of predictive quality of the machine models

Both lumped-element and FEM based multibody models can be used for different dynamical and performance analysis of the semicon machine, including control simulations. The engineers can use these analysis to evaluate their designs at the earliest stages of product development or investigate existing performance issues. In the following, we compare simulation results with measurements to evaluate capability of the models to quantitatively predict position dependent dynamics and motion control performance. For confidentiality reasons, we do not display numerical data in the plots below.

On the left-hand side in Figure 4, we show magnitude plots of the frequency response functions measured at three distinct locations of the XYZ-motion stage: location 1 is in the middle of the X-stroke and the other two are nearby the lower and upper mechanical limits of the X-axis. These plots show the most profound resonance peaks for the X-motion axis and reveal their position dependency: the resonance frequencies and their damping characteristics do change with the X-location. In the same figure, on the right-hand side, we show the corresponding magnitude plots that are simulated using the Matlab/Simulink/Simscape Multibody™ model of the bonding machine. Circles of different colors mark the anti-resonances and resonances that correspond to each other in the measurements and simulations. Apparently, the model reasonably well reproduces these dynamics and their position dependency.

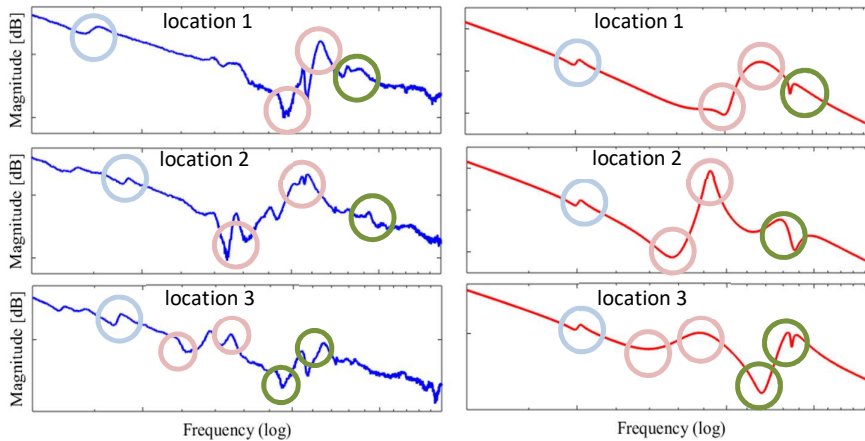


Figure 4. Magnitude plots of transfers from X-motor force to X-displacement at three locations of the XYZ-stage: measured (blue) and simulated (red).

In Figure 5, we show the measured and simulated magnitude characteristics of the transfer from the Z-motor force to the Z-displacement. With these plots, we can demonstrate quality of modeling the dynamics that are caused by structural deformations. These dynamics are marked by the circles. The simulated data are obtained using two models of the bonding machine: the middle plot is generated using the the Matlab/Simulink/Simscape Multibody™ model with the FEM representation of the structurally deformable part of the bonding tool and the plot on the right-hand side is obtained using the Hyperworks/MotionView model of the semicon machine. By inspection of these plots, one can notice a good match between the measured and simulated data, which verifies ability of both models to properly reconstruct dynamics of structural flexibility.

Finally, we evaluate predictive performance of the multibody models in control simulations using the multibody modeling approach explained in Section 3.1. In Figure 6, we show measured and simulated position errors for the X-axis of the motion stage achieved with two settings of the feedforward controller. As expected, lower errors are obtained with a better feedforward tuning. Although the measured and simulated errors are not identical, these are rather similar especially in terms of their amplitudes. That illustrates

satisfactory predictive performance of the multibody simulations, which is a direct consequence of capturing integral machine dynamics including flexibilities, dynamical couplings, and nonlinearities. It is important to mention that these models are developed by junior engineers [9-11] who had no prior experience with multibody modeling of such a complexity. Being greatly facilitated by advanced software tools with high level of modeling automation, the juniors produced functional models that enable rigorous design qualifications and optimizations of high fidelity.

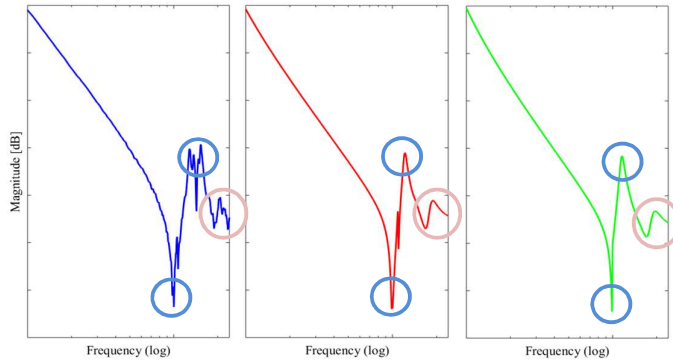


Figure 5. Magnitude plots of transfers from Z-motor force to Z-displacement of the XYZ-stage: measured (blue), simulated using Simscape Multibody™ model with FEM representation of the deformable part (red), and simulated using the Hyperworks/MotionView model (green).

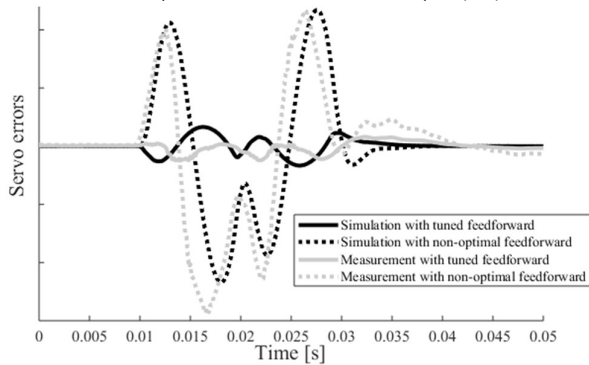


Figure 6. Simulated vs measured position errors achieved with non-optimal and improved feedforward tunings for the X-motion of the the XYZ-stage.

5. Conclusions and outlook

The software framework for integral modeling and simulation of semicon machines is presented which incorporates state-of-the-art commercial tools – Matlab/Simulink/Simscape Multibody™ and Hyperworks/MotionView. The Simscape Multibody™ enables generation of lumped element multibody models with a high level of modeling automation. Its key limitation is the lack of direct support to integration of FEM models of structurally deformable parts. The FEM models can directly be imported in Hyperworks/MotionView, which enables analysis and control simulations of integral dynamics including structural flexibilities, position-dependent dynamics, nonlinear couplings, etc. The modeling automation helps reducing occurrences of the modelling errors and enables even non-specialists in dynamical modeling to create models that allow machine design optimizations, root-cause analysis and troubleshooting of performance and reliability issues. This is demonstrated by multi-body modelling of a commercial bonding machine which is performed by students at ASM. Their limited professional experience has no impact on quality of their modelling results, which is demonstrated by convincing matches between the simulations and measurements obtained on the physical machine. In the future, efforts will be made towards automated tuning of model parameters. For this, we consider optimal matching of simulations with measurements and creation of a library of verified models of different machine components.

References

- [1] Steinbuch M, "Mechatronics disrupted?", <http://www.mechatroniamachinebouw.nl>, 2015.
- [2] Kostić D et al., 2016 High-tech in Evolution: Transition from Mechatronics Authority to Robotics Excellence *Mikroniek* **56** No. 3, 5-11
- [3] Nijmeijer H and Van der Schaft A, *Nonlinear Dynamical Control Systems*, Springer, New York, 1990.
- [4] Pavlov A et al., *Uniform Output Regulation of Nonlinear Systems: A convergent Dynamics Approach*, Birkhäuser, Boston, 2005.
- [5] Shabana A A, *Dynamics of Multibody Systems*, Cambridge University Press, Cambridge, 2013.
- [6] Bauchau O, *Flexible Multibody Dynamics*, Springer Netherlands, 2011.
- [7] Géradin M and Cardona A, *Flexible multibody dynamics: a finite element approach*, John Wiley, New York, 2001.
- [8] ASM Center of Competency, <http://alsi.asmpt.com>
- [9] Van Es R M J, Development of a multibody model of a wire bonder, DCT internship report, 2017.
- [10] Fethke T, Integration of FEA Models of Structurally Deformable Parts Into LE Models of Wire Bonder Dynamics, DCT internship report, 2018.
- [11] Zwaans L W A, Framework for model-based development of multibody systems with deformable parts, DCT MSc report, 2018.
- [12] Simscape Multibody toolbox of Matlab, <https://nl.mathworks.com/products/simmechanics.html>
- [13] MotionView by Altair HyperWorks, <https://altairhyperworks.com/product/motionsolve/motionview>
- [14] SolidWorks CAD software, <https://www.solidworks.com>
- [15] Onshape cloud based CAD tool, <https://www.onshape.com>