Mountain bicycle frame testing as an example of practical implementation of hybrid simulation using RTFEM

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Abstract

The paper presents a practical implementation of hybrid simulation using Real Time Finite Element Method (RTFEM). Hybrid simulation is a technique for investigating dynamic material and structural properties of mechanical systems by performing numerical analysis and experiment at the same time. It applies to mechanical systems with elements too difficult or impossible to model numerically. These elements are tested experimentally, while the rest of the system is simulated numerically. Data between the experiment and numerical simulation are exchanged in real time. Authors use Finite Element Method to perform the numerical simulation. The following paper presents the general algorithm for hybrid simulation using RTFEM and possible improvements of the algorithm for computation time reduction developed by the authors. The paper focuses on practical implementation of presented methods, which involves testing of a mountain bicycle frame, where the shock absorber is tested experimentally while the rest of the frame is simulated numerically.

Keywords: hybrid simulation, hybrid testing, real time finite element method, hardware in the loop

1. Introduction

Hybrid simulation (also referred as hybrid testing, or hardware-in-the-loop simulation) is a technique for investigating dynamic material and structural properties of mechanical systems by performing numerical analysis and experiment at the same time. Two models of the tested system are created: the experimental model, which is a physical part of the system, and the analytical model, which is a numerical representation of the rest of the tested system. Mechanical systems of deformable bodies are taken into consideration. In the experiment the physical part is mounted to actuators and strained by them exactly as it would be strained as a part of the whole system. In order to make it possible, a simultaneous numerical analysis is performed and data between experiment (from sensors) and numerical analysis are exchanged in real time. The typical applications of hybrid simulation are mechanical systems with elements that are too difficult or even impossible to model numerically. In hybrid simulation these elements are tested experimentally [1,4].

The authors use Finite Element Method (FEM) in the numerical analysis to model the mechanical system because of broad range of possible applications and a well-known process of creating FEM models.

As mentioned before, the data between analysis and experiment must be exchanged in real time. This implies the FEM computations also to be performed in real time. Real-time means a previously specified time frame in which the computations must be reliably and, without fail, performed and the results made available. As FEM is a very computationally demanding method, it's implementation in real time is difficult, however possible and called Real Time Finite Element Method (RTFEM).

2. RTFEM Algorithm

2.1. Equation of motion

The algorithm of hybrid simulation using RTFEM is based on the equation of motion:

$$\mathbf{M^A}\ddot{\mathbf{u}} + \mathbf{C^A}\dot{\mathbf{u}} + \mathbf{K^A}\mathbf{u} + \mathbf{r^E} = \mathbf{f} \tag{1}$$

where $\mathbf{M^A}$, $\mathbf{C^A}$ and $\mathbf{K^A}$ are the mass, damping and stiffness matrices of the analytical part of the system, respectively, $\mathbf{u}$ is the displacement vector, $\mathbf{r^E}$ is the vector of forces developed in the physical part during experiment and $\mathbf{f}$ is the excitation force vector [2,6].

The algorithm of hybrid simulation is iterative therefore Eqn (1) is solved for each time step. In each time step i the displacement $\mathbf{u_i}$ is imposed on the physical part, the developed forces $\mathbf{r^E}$ are measured and displacement for the next time step $\mathbf{u_{i+1}}$ is computed from Eqn (1) [1,4].

2.2. Explicit and implicit methods

Equation (1) can be solved in an iterative approach using implicit or explicit methods [6,7].

In explicit methods the displacement in the next time step is computed using only data from the current time step. In implicit methods the displacement in the next time step is computed using data from current and next time step, which in the context of hybrid simulation is a considerable drawback, as the forces that will be generated in the physical part in the next time step must be at least roughly estimated. Therefore using explicit methods is highly recommended in hybrid simulation, however often not possible because they are only conditionally stable and the stability condition limits the time step. When the largest allowable time step is less than computational time for a single

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step, real-time computations are not possible. In such case implicit methods should be utilized because they often are unconditionally stable [4,7].

3. Applied improvements to the algorithm

3.1. Mode superposition

Implementing mode superposition to the computational part of the hybrid simulation allows significant model order reduction. It consists of transforming the displacement coordinates to modal coordinates. This procedure requires to solve the generalized eigenproblem, which is very computationally demanding however performed before the hybrid simulation. The order reduction is obtained because usually only first few free vibration mode shapes are used for the coordinates transformation. It leads to loss of accuracy, therefore the number of mode shapes to use for transformation (equal to number of Degrees of Freedom of the reduced model) must be chosen wisely, for the loss of accuracy to be insignificant.

Another substantial advantage of implementing mode superposition is that the less mode shapes are used for transformation, the bigger possible time step in explicit methods. In other words implementing mode superposition may allow to use explicit methods in real time in cases where it was not possible.

Detailed description of hybrid simulation algorithm with mode superposition and requirements for its implementation can be found in [2].

3.2. FPGA support

Normally all the computations are performed in Central Processing Unit of the microcontroller controlling the actuators in hybrid simulation. The improvement is to perform the most computationally demanding operations (solving the system of equations in each iteration) using FPGA.

FPGA means field-programmable gate array, and it is a configurable integrated circuit that contains an array of programmable logic blocks and interconnects. The advantages of FPGA are flexibility, highly parallel processing, high performance and reliability. Project Catapult by Microsoft reveals the great potential of FPGA computations [5].

Details about adapting the hybrid simulation algorithm for FPGA support are described in [3].

4. Experiment

Steel frame of a mountain bicycle (presented in fig. 1) is tested in hybrid simulation using RTFEM.

The FEM model is a plane frame, modelled by 27 finite elements. The rear shock absorber (element 17) is the physical part that is tested experimentally. The shock absorber is mounted in dynamic materials testing machine Instron ElectroPuls E10000. The machine is controlled by microcontroller National Instruments myRIO, with FEM model implemented in the algorithm.

5. Conclusion

Hybrid simulation is a useful method for mechanical structures and systems with elements that are difficult to model numerically (e.g. with highly nonlinear characteristics), like the shock absorber of the presented frame.

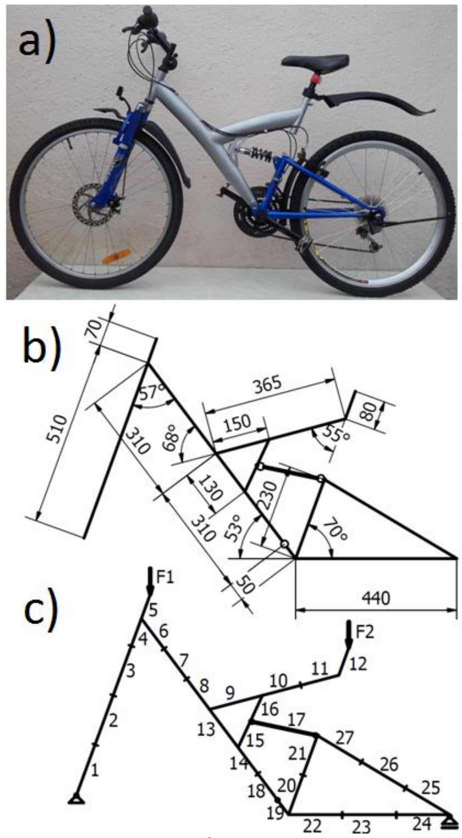

Figure 1: Mountain bicycle frame: a) photograph, b) CAD model, c) FEM model

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