Computer-aided analysis of rigid and flexible multibody systems

Today challenges and Applications

Today Challenges
- Multiphysics modelling and simulation
- Multibody systems with flexible bodies
- Optimization
- Real time computation/control
- Identification & inverse dynamics
- Biomechanics
- Vehicle dynamics
- Education

Multiphysics: mechatronics
- Integrated analysis:
  - Mechanism
  - Actuators
  - Sensors
  - Controller

High-speed machines
Cars (suspension, ESP...)

Integrated analysis:
Mechanism
Actuators
Sensors
Controller
Multiphysics: micro-mechatronics
- Integrated analysis and design
  - Multibody dynamics
  - Electronics
  - Hydraulics
  - Pneumatics
  - Electrical circuits
  - Piezoelectricity
  - Magnetics
  - Thermics...
- Next step: micro-mechatronics

Multiphysics modeling: MBS + ELEC (1)
- Problem: Collab: Bombardier
  - Unified dynamic modeling of MBS and electrical actuators
- Solution:
  - Equational level coupling: Electromechanical Lagrange equations
  - Symbolic implementation via recursive approach (MBS + ELEC)
    \[ L = L + L' \]
    \[ \frac{d}{dt} \left( \frac{d}{dt} q \right) - \frac{d}{dt} \mathbf{u} = 0 \]
- Application:
  - Coupling analysis between asynchronous actuators (electrical frequency) and bogie chassis fatigue (mechanical frequency)

Multiphysics modeling: MBS + ELEC (2)
- Problem: Collab: Automatic systems
- Solution:
  - Equational level coupling: Electromechanical Lagrange equations
  - Symbolic implementation via recursive approach (MBS + ELEC)
- Application:
  - Coupling analysis between asynchronous actuators (electrical frequency) and parking gate flexibility (mechanical frequency)
Multiphysics modeling: MBS + « HYDRAULICS »

- **Problem**: Unified dynamic modeling of MBS and Hydraulic circuits
- **Solution**: Equational level coupling including « hydraulic » constraints
  - Real time simulation (Symbolic + C compiled Simulink models)
- **Application**: Dynamic performance analysis of a new integral suspension « Kinetic »

Multiphysics modeling: MBS + « PNEUMATICS »

- **Problem**: Unified dynamic modeling of MBS and Pneumatic circuits
- **Solution**: New pneumatic models: algebraic/differential/finite difference ...
- **Application**: railway secondary suspension

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Highly flexible systems

Solar panels deployment with tape-spring hinges

OUFTI-1 Student CubeSat

10x10x10 cm & 1 kg

2 deployable antenna

Deployable structures

- Large antenna
- No axial symmetry
- 1 kinematic dof!
- Slow deployment (15 min)
- 1-g test rig \(\Rightarrow\) 0-g behaviour?

Ref.: Géradin & Cardona 2001
Deployable structures

- FE mechanical model
  - Flexibility (struts + panels)
  - Local stiffnesses & friction
  - Inertial forces = negligible
  - 1400 equations

- Kinematic analysis
  - Imposed angle of the central body
  - Driving torque?
  - Forces in the struts?
  - Hinge angles?

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Deployable structures

a) 1-g model ⇒ experimental validation
b) 0-g model ⇒ accurate prediction
MBS with flexible beams

- Problem:
  - Modeling MBS with flexible beams
  - with large MBS motions
  - Fully Symbolic Modeling of such Systems

- Solution:
  - Generalisation of MBS formalisms (e.g., Recursive method + Timoshenko beam)
  - Shape functions: monomials versus FEM approaches

- Application:
  - Benchmarks of the “MBS” community:
  - ➔ Rotating beams, flexible slider–crank...

Piezoelectric actuation

- Problem:
  - MBS Modeling of the “mechano-mechanical” transmission of a piezoelectrical actuator
  - Performance evaluation of a piezoelectrical actuator (slider on a beam) using a propagating wave induced in an aluminium beam

- Solution:
  - MBS model of a flexible beam + actuators
  - Contact (friction/Hertz) model between the deformed beam and the slider

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Multibody System Optimization

- Optimization of MBS
  - Cost function: "kinematic" or "dynamic" performances
  - Design parameters: geometry, topology, physical properties, control
  - Optimization algorithms: deterministic or stochastic methods
  - Sensitivity analysis: finite difference or analytical methods
  - Existence of local optima (non-convex problems)
  - Problem of computational time

Optimization of MBS components

Optimal design of MBS components?

Develop topology optimization for MBS components:

Optimization: Sensitivity analysis

Gradient-based optimization with many parameters

- Finite difference: 1 (or 2) simulation per parameter
- Automatic differentiation
- Semi-analytical approach
  - direct differentiation
  - adjoint variable method
Optimization: Sensitivity analysis

Importance of an efficient sensitivity analysis:

- Test problem with (only) 60 design variables
- Finite difference (61 simulations)
  \[ \Rightarrow \text{CPU time} = 141 \text{ s} \]
- Direct differentiation (1 extended simulation)
  \[ \Rightarrow \text{CPU time} = 16 \text{ s} \]

Moreover, the direct differentiation method leads to higher levels of accuracy.

Morphological Optimisation

- **Problem:**
  - Determination of the optimal geometry and morphology of planar mechanism (ex: // robot) for a given task

- **Solution:**
  - Development of specific tools to deal with closed-mechanisms singularities
  - New optimisation strategies (combining deterministic & stochastic methods)

- **Application:**
  - Kinematics: parallel robot isotropy optimisation (next slide)
  - Geometry: search of local minima of planar mechanisms (next slide)

Morphological Optimisation

- **Animation**
  - Kinematics: parallel robot isotropy optimisation
Morphological Optimisation

- **Animation**
  - Geometry: search of local minima of vehicle steering linkage
    (Ackermann-based optimisation criteria)

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**Real time applications**

**CPU time saving strategies**

- More efficient formulations of the equations of motion (e.g. recursive methods)
- Eliminate « small terms » in the equations of motion
- Model reduction techniques
- More efficient time integration algorithms
  - implicit vs. semi-implicit methods
  - use an approximated iteration matrix
**Real time applications: control**

Motion & vibration control of a flexible manipulator

Mechanism
- 2 flexible links (3 m long)
- Vertical plane

Actuators
- Hydraulics
- Parallel mechanism

Sensors
- Linear collocated sensors
- Tip accelerometers

RALF (Georgia Tech)

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**Real time applications: control**

- Large workspace
- Natural frequencies: 3 - 12 Hz

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**Real time applications: control**

Model-based control: Response to a tip force

Simulation

Fast control off

Experiment

Fast control on
Dynamic identification

- **Problem**: Identification of mass, mass centers and inertia matrices of MBS

- **Solution**:
  - Use of inverse dynamic models (robots) and reaction models (human body)
  - Measure of the joint/reaction forces and of the motion ($q, \dot{q}, \ddot{q}$)
  - Symbolic combination of dynamic parameters (barycentric approach)
  - Linear regression $Q = \phi \cdot A$ (for exciting trajectories)

- **Application**:
  - **Human**: reaction model for very specific motion (but tricky – weak accuracy)
  - **Robots**: dynamic calibration – Inverse-Reaction models « enrichment »

Dynamic identification

- **Robot calibration**: Dynamic parameter estimation combining **internal** and **external** models

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Dynamic identification

- Human body « calibration »

- The Reaction Model
  \[ \mathbf{Q}_r = \Phi((\mathbf{q}, \dot{\mathbf{q}}), \delta) \]
  where
  - \( \mathbf{Q}_r \): reaction forces and torques of the ground on the system
  - \( \delta \): minimal set of parameters for the reaction model

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Biomechanics (1)

- Problem:
  - Quantification of muscle forces in the human body

- Solution:
  - Mathematical optimization of the motion kinematics (exper. MBS model)
  - Deterministic computation of the joint « net » torques via inverse dynamics
  - Muscle forces computation via optimization, including EMG measurements

- Application:
  - Kinematics: walking, getting up (from a seat)
  - Dynamics: Muscle force quantification (arm flexing with dumbbells)
Biomechanics (12)

Problem - Application:
- Kinematic study/verification of a rehabilitation robot for hemiplegic patients
- Computation of joint efforts for various configurations

Solution:
- Complete 3D MBS kinematic model: shoulder - robot - arm - shoulder
- Inverse dynamic model (with virtual force sensors as input)

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Landing gears

- Different phases
  - Deployment / retraction
  - Ground impact
  - Rolling
  - Breaking
  - Taxing
- Multidisciplinary approach
  - Deformable mechanism
  - Tyre
  - Hydraulics (shock-absorber, brake, steering)
  - Active / semi-active control

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**Tangential contact forces**

- Elastic deformation of wheel and rail
- Pseudo-slips
- Contact zone transition
- Longitudinal force
- Lateral force
- Aligning moment
- Creepages (slips)
- Normal force
- Contact geometry

**Stability – kinematic yaw**

The wheelset naturally follows the rail if $V_f$, $r_f$ et $r_d$

- $V_f$, $r_f$ et $r_d$
- $V_l$, $r_l$
- $V_k$, $r_k$

But oscillates with a wavelength

$$L = \frac{V}{f} = 2\pi \sqrt{\frac{r_l}{\delta}}$$

(Klingel formula (no slip))

**Root locus of a bogie**

There exists a critical speed!
Bogie stability - unstability

Stable behavior \((V < V_{critical})\)

Unstable behavior (limit cycle)

Tramway of Minneapolis

Rigid wheelsets

Independent wheels

Unconventional railway bogies

- **Problem**: Multibody modeling of an articulated bogie equipped with independent wheels
  
  \(\Rightarrow\) How to constraint a profiled wheel on a profiled rail?

- **Solution**: Use of a geometrical wheel and additional auxiliary variables
  
  Loop closure: Dichotomic method + Newton-Raphson algorithm

- **Application**: Stability analysis of the T2000 tramway of Brussels (equipped with the BA2000 bogie)
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“MBS-based” student project

Given...

- a real system
- a CAD system
- programming tools

...produce

- system animation
- system analysis
- system parameterization

An opportunity for Belgian “Multibodynicians”

Multibody Dynamics 2011
4th July - 7th July 2011, Brussels, Belgium