Model Order Reduction Based Simulation and Optimization of Large Bore Internal Combustion Engines

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Abstract

This thesis is intended for computational engineers and mathematicians who work on multibody simulation, model order reduction, tribology and virtual internal combustion engines. Interconnected modules are used within a simulation workflow to describe a large bore internal combustion engine. The modules are responsible for the generation of finite element discretized mechanical models, model order reduction, and the elastohydrodynamic simulation of flexible multibody systems. The theoretical background of the different modules is presented, and it is shown how to connect them to represent an internal combustion engine. To reduce the computational effort, an optimal scheduling of the modules by a genetic algorithm is investigated. Applications of the simulation workflow are discussed for the 4-stroke diesel engine 20V28/33D and the spark ignited 4-stroke gas engine 20V35/44G. Different convergence analyses, numerical experiments, and optimizations are performed. Algorithms and recommendations for an efficient model order reduction and multibody simulation are proposed. This includes an optimal configuration of the integrator, use of the proper orthogonal decomposition method, parameter dependent model order reduction, time varying model order reduction, a proper orthogonal decomposition based wear simulation, and an efficient gradient calculation of the mean friction loss based on the adjoint approach. Finally, two friction loss optimizations of the running-in process and operational stage are performed.

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Contents

Nomenclature

Abbreviations

ACT	Actuator
AD	Automatic differentiation
ADJ	Adjoint approach for gradient calculation
ATOL	Absolute tolerance
BAX	Axial bearing
BDC	Bottom dead center
BEA	Bearing
BW	Finite backward difference approximation
CA	Crank angle
CAD	Computer aided engineering design
CB	Craig Bampton method
CEN	Finite central difference approximation
CMS	Component mode synthesis method
COU	Coupling
CPU	Central processing unit
CRA	Crank
CRC	Crankcase
CRD	Connecting rod
CRS	Crankshaft
CRT	Cranktrain
DAE	Differential algebraic equation
DOF	Degrees of freedom
EHD	Elastohydrodynamic
EHL	Elastohydrodynamic lubrication
EMBS	Elastic multibody system
FE	Finite elements
FEM	Finite element method
FLW	Flywheel
FMI	Functional mockup interface
FW	Finite forward difference approximation
GA	Genetic algorithm
GUI	Graphical user interface
HYM	Hydrodynamic mesh
JOU	Journal

LTI	Linear time-invariant system
MBS	Multibody system or multibody simulation
MDOF	Master degree of freedom
MEA	Measurement
MIMO	Multi-input-multi-output
MOR	Model order reduction
MPH	Morphing
ODE	Ordinary differential equation
PAR	Principal axis reduction
PMOR	Parametrized model order reduction
POD	Proper orthogonal decomposition (method)
PODPARS	Proper orthogonal decomposition based on PAR simulation
RBE-2	Rigid body element type 2 (rigid behavior)
RBE-3	Rigid body element type 3 (elastic behavior)
RCPSP	Resource-constrained project scheduling problem
RED	Reduction
RPM	Rotations per minute
RTOL	Relative tolerance
RUN	Running surface of a bearing
SGPOD	Sparse grid proper orthogonal decomposition
SIM	Simulation
SISO	Single-input-single-output
STM	Structural mesh
SVD	Singular value decomposition
TDC	Top dead center
TDC (fire)	Top dead center fire
TRA	Transient approach for gradient calculation
TVD	Torsional vibration damper
VMOR	Time varying model order reduction
WC	Working cycle which has the length of 720° for 4-stroke engines
ZWA	Flexible position data of a body
ZWB	Flexible acceleration data of a body
ZWG	Flexible velocity data of a body
ZWS	Rigid body position, velocity and acceleration data

Roman Symbols

A	Contact area
A	System matrix within an LTI
B	System matrix within an LTI
b	Force density
B_2	Input matrix of a second order system
C	System matrix within an LTI
c	Constraint within an optimization
C_1, C_2	Output matrix of a second order system

C_j	Completion time of the module M_j within a process P
c_{COU}	Stiffness property of the coupling
c_{TVD}	Stiffness property of the torsional vibration damper
C_{max}	Execution time of a process P
D	Diameter
ΔD	Absolute diametrical clearance
$\mathbf{D}$	Diagonal matrix of the weights α_i
D_e	Damping system matrix
E	Precedence constraints of a process
E	System matrix within an LTI
E	Young's modulus
E_c	Effective modulus of elasticity
F	Applied force on a body
F	Parameter-dependent DAE system
f	Applied force
f	Density function (statistical or empirical)
f	Frequency
f_1	Force of a bearing in vertical direction
f_2	Force of a bearing in horizontal direction
F_e	Applied force vector acting on a flexible body
F_m	Force vector on the master degrees of freedom x_m
F_N	Normal load
F_s	Force vector on the slave degrees of freedom x_s
F_{ce}	Centrifugal force acting on a body
F_{co}	Coriolis force acting on a body
F_{gy}	Gyroscopic force acting on a body
G	Jacobian matrix of the constraint vector g
G	Objective function (integral based)
g	Objective function
g	Vector of holonomic constraints
GEN	Number of generations within a GA
gen	Generation of a population within a GA
H	Hardness of a material
H	Hilbert space
H	Transfer function
h	Local film thickness
h	Wear depth
$\bar{h}$	Average local gap
h^*	Nominal film thickness
H^m	Sobolev space
H_k	Hierarchical sampling of level k
h_{min}	Minimum gap
I	Time interval $I = [t_0, t_f]$

i	Index
$\mathbf{I}$	Identity matrix
I_c	Set of constraints
i_j	Input vector of the module M_j
$i_{\max}$	Termination condition of an optimization: Maximum number of iterations
J	Weighted projection error
j	Index or see M_j
K	Constant within the Greenwood and Tripp contact model
K	Set of renewable resources
K	Wear coefficient
k	Index or a renewable resource
K_e	Stiffness system matrix
l	Number of basis vectors within a reduction method
L^2	Function space of quadratically integrable functions
L_j, l_j	Link with an l_j:1 relation
l_H	Number of steps in a hierarchical reduction
M	Mass matrix
M_e	Mass system matrix
M_j	Module
m_j	Dimension of the output vector of the module M_j
N	Spatial location of a node
N_0	Initial spatial location of a node
n_c	Number of constraints of an optimization
n_e	Dimension of the finite subspace V^h used for discretization
n_g	Number of constraints of a DAE
n_j	Dimension of the input vector of the module M_j
n_p	Dimension of a parameter p
n_s	Nominal speed of an engine
n_u	Dimension of an input of a system
n_v	Number of constraint violations
n_w	Maximum interations in a wear algorithm
n_x	Dimension of a state x
n_y	Dimension of an output of a system
n_z	Dimension of a state z
n_Ω	Spatial dimension of a domain
n_{cs}	number of calculated schedules
o_j	Output vector of the module M_j
P	Friction loss
P	Process which couples modules J with links L
p	Parameter within the parameter space $\mathbb{R}^{n_p}$
p	Pressure
$\bar{P}$	Mean friction loss

$\bar{p}$	Specific load
P_i	Input power of an engine
p_l	Lower bound vector of the box constraint of an optimization
p_m	GA parameter: mutation rate
P_o	Output power of an engine
P_r	Friction loss of an engine
p_r	GA parameter: random selection
p_u	Upper bound vector of the box constraint of an optimization
P_α	Approximation of the wear friction loss
P_{wear}	Friction loss that takes wear into account
P_{co}	Contact friction loss
p_{co}	Contact pressure
P_{hy}	Hydrodynamic friction loss
p_{hy}	Hydrodynamic pressure
p_{max}	Maximum pressure
POP	Size of a population within a GA
Q	Schedule of a process, definig the execution order of modules
q	Generalized coordinate of a reduced system
r	Correction term / residual
r	Relative convergence value
R_k	Number of available units of the resource k
r_{jk}	Number of required resource k of the module M_j
S	Safety factor
s	Sliding distance during contact
s	Speed-up between one approach and its reference concerning CPU time or number of function calls
S_i	Shape vector used for morphing
S_j	Start time of the module M_j within a process P
T	Period length
T	Task
T	Temperature of a bearing at the inlet
t	Time t within the time interval $I = [t_0, t_f]$
t_0	Start time t_0 of the time interval $I = [t_0, t_f]$
t_f	Final time t_f of the time interval $I = [t_0, t_f]$
t_j	Execution time of the module M_j
T_σ^j	Moment of a transfer function H
T_{ij}	Transformation matrix between two states x_i and x_j
u	Input of a system
u	Local deformation of an elastic structure
u	Surface velocity within the Reynolds Equation
$\mathbf{U}$	Unitary matrix within a SVD
u_i	i-th left singular vector of $\mathbf{U}$
V	Projection matrix within the Petrov-Galerkin projection

V	Wear volume
v	Intermediate variable within a DAE
v	Surface velocity within the Reynolds Equation
$\mathbf{V}$	Unitary matrix within a SVD
V^h	Finite subspace of V
v_i	i-th right singular vector of $\mathbf{V}$
$V_k^{(1)}$	Sparse grid of level k
$V_k^{(\infty)}$	Full grid of level k
W	Projection matrix within the Petrov-Galerkin projection
W	Width
$\mathbf{W}$	Weight matrix in the norm $< u, v >_{\mathbf{W}}$
$W^{m,2}$	Sobolev space
W_α	Multi-dimensional sampling used for sparse grids
W_k	Sampling used for sparse grids
X	Snapshot matrix
x	State variable of a second order system
x_0	Initial condition of a state x within an ODE
x_i	Data vector (column) of a snapshot matrix X
x_m	Master degrees of freedom within a state x
x_s	Slave degrees of freedom within a state x
x_l	Lower bound of a box constrained space
x_u	Upper bound of a box constrained space
$X_{x,\dot{x},\ddot{x}}$	Snapshot matrix which includes the data x, $\dot{x}$, and $\ddot{x}$
$X_{x,\dot{x}}$	Snapshot matrix which includes the data x and $\dot{x}$
X_x	Snapshot matrix which includes the data x
y	Output of a system
Z	Non-singular matrix used for the description of translations and rotations
z	State variable of a first order system
z_0	Initial condition of a state z within a DOE

Greek Symbols

α	Factor of the mass matrix within Rayleigh damping
α	Multi-index
α	Weight of the P_α method
β	Factor of the stiffness matrix within Rayleigh damping
χ	Indicator function used for VMOR
δt	Integrator output increment
δ	Combined roughness of two surfaces
δ_i	Roughness amplitude of surface i
ϵ	Heuristic information
ϵ	Linearized strain tensor
ϵ_2	Squared heuristic information
ϵ_c	Tolerance for a constraint to define its state

ϵ_h	Absolute local contour error
$\|\epsilon_h\|$	Maximum contour error
ϵ_p	Perturbation in finite differences
$\epsilon_{2,\Delta}$	Square root of the error of the heuristic information ϵ_2
ϵ_χ	Threshold within VMOR
ϵ_Δ	Error of the heuristic information ϵ
ϵ_σ	Weighted singular value
$\epsilon_{*,f}$	Termination condition of an optimization: ATOL or RTOL for the target function
$\epsilon_{*,p}$	Termination condition of an optimization: ATOL or RTOL for the parameters
$\bar{\epsilon}_P$	Mean friction loss error
$\bar{\epsilon}_{P,\max}$	Overall maximum error of $\bar{\epsilon}_P$
ϵ_P	Local relative friction loss error
ϵ_r	Tolerance for the relative convergence value
η	Dynamic lubricant viscosity
η	Efficiency
Γ	A dγ-measurable subset of $\partial\Omega$
γ	Outer normal vector of Ω
λ	Lagrange multiplier
λ	Lamé constant within Young's modulus E and Poisson's ratio ν
λ	Wear coefficient
μ	Lamé constant within Young's modulus E and Poisson's ratio ν
μ	Parameter mean within a normal distribution
μ_c	Coefficient of friction
ν	Poisson's ratio
Ω	Spatial domain
ω	Angular velocity
$\Omega_{0,1}$	Unit box constraint space
Ω_Γ	A representative domain of the bearing edges
$\Omega_{\mathrm{l,u}}$	Box constraint space
ω_j	Eigenfrequency of a system
Φ	Finite basis of the finite subspace V^h
Φ_i	Basis vector of the finite subspace V^h
ϕ_i	Mode shape
Φ_{kl}^p	Pressure flow tensor
Φ_{kl}^s	Shear flow tensor
Ψ	Relative clearance
ψ	Orthonormal basis vector of $\mathcal{V}^l$
ψ_i	Orthonormal vector of POD basis
ρ	Density
Σ	Diagonal matrix of singular values σ_i
Σ	Finite-dimensional dynamical system

σ	Cauchy stress tensor
σ	Expansion point of a moment T_σ^j
σ	Parameter standard deviation within a normal distribution
σ	Statistical parameter root mean square
σ_i	i-th singular value
σ_i	Hankel singular value
τ	Surface stress
θ	Active basis index within VMOR
Φ_j	Eigenmode of a system

Mathematical Symbols

$\bar{\cdot}$	Mean operator
$\Delta[\,\cdot\,]$	Difference of $[\,\cdot\,]$ compared to its initial state $[\,\cdot\,]_0$
δ_{ij}	Kronecker symbol
$\hat{\cdot}$	Approximation operator
$\mathbb{P}$	Parameter space of an optimization problem
$\mathcal{C}^k(I)$	Class of k times continuously differentiable functions with respect to time
$\mathcal{F}$	Fundamental solution matrix
$\mathcal{I}$	Population of a GA
$\mathcal{K}_j$	Krylov subspace
$\mathcal{K}_j^2$	Second-order Krylov subspace
$\mathcal{L}$	Laplace transformation
$\mathcal{L}(\psi, \lambda)$	Lagrange functional of an optimization problem
$\mathcal{M}^k$	Set of vertices ($k = 0$), edges ($k = 1$), faces ($k = 2$), and the primary topological elements ($k = 3$)
$\mathcal{N}$	Function used for mesh morphing
$\mathcal{P}$	Controllability Gramian
$\mathcal{Q}$	Set of feasible schedules
$\mathcal{Q}$	Observability Gramian
$\mathcal{T}$	Topology of a mesh
$\mathcal{V}$	Space spanned by a data vector x
$\mathcal{V}$	Subspace spanned by the projection matrix V
$\mathcal{W}$	Subspace spanned by the projection matrix W
$\mathfrak{d}$	Individual daughter generated by crossover within a GA
$\mathfrak{f}$	Individual father used in crossover within a GA
$\mathfrak{i}$	Individual within a GA
$\mathfrak{m}$	Individual mother used in crossover within a GA
$\mathfrak{s}$	Individual son generated by crossover within a GA
∇f	Gradient of a function f
$\{\cdot\}\vert_\xi$	Notation of restriction (i.e. $\{a+b\}\vert_\xi$ is the short form of $a_\xi + b_\xi$)