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M.Sc. Marcel König,
Hamburg

Partitioned Solution Strategies for Strongly-Coupled Fluid-Structure Interaction Problems in Maritime Applications

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Many engineering applications are governed by coupled multifield phenomena. In this thesis, a partitioned solution approach is followed to solve these kind of problems, which does not only enable the use of different discretization schemes for each of the subproblems but also allows to reuse specialized and efficient solvers, which enhances modularity, software reusability, and performance. A framework for the partitioned analysis of general multifield problems is proposed and implemented in the generic software library comana, which is verified against various benchmark problems and successfully applied to sophisticated fluid-structure interaction problems from the maritime industry.

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Contents

List of Acronyms

AAA	Almost always use `auto`
AABB	Axis-aligned bounding box
ALE	Arbitrary Lagrangian-Eulerian
APDL	ANSYS parametric design language
API	Application programming interface
BEM	Boundary element method
BMWi	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy)
CFD	Computational fluid dynamics
COG	Center of gravity
CPU	Central processing unit
FE	Finite element
FEM	Finite element method
FSI	Fluid-structure interaction
FV	Finite volume
FVM	Finite volume method
HF	High frequency
HyStOH	Hydrodynamische und strukturmechanische Optimierung eines Halbtauchers für Offshore-Windenergieanlagen (Hydrodynamic and structural optimization of a floating platform for offshore wind turbines)
JONSWAP	Joint North Sea Wave Project
LF	Low frequency
MPI	Message passing interface
MVP	Most vexing parse
ODR	One definition rule
OWT	Offshore wind turbine
pImpl	Pointer to implementation
POD	Plain old data
RAII	Resource acquisition is initialization
RANS	Reynolds-averaged Navier-Stokes
RAO	Response amplitude operator
RBF	Radial basis function
RVO	Return value optimization
SFINAE	Substitution failure is not an error
VOF	Volume of fluid

List of Symbols

Nomenclature

In this thesis, the following notation for the distinction of scalars, vectors, tensors, and matrices is introduced. Scalars s are denoted in italic font. Vectors $\boldsymbol{v}$ from the Euclidean space as well as second-order tensors $\boldsymbol{T}$ defined as linear maps between vector spaces are typeset in bold italic font. Bold calligraphic symbols are used to represent tensors $\boldsymbol{\mathcal{C}}$ of order higher than two. While "short" local discrete vectors $\boldsymbol{v}$ and matrices $\boldsymbol{M}$ are typeset in bold italic font, "long" global discrete vectors $\mathbf{v}$ and matrices $\mathbf{M}$ are denoted by an upright bold symbol.

Symbol	Description
$\mathrm{card}(\mathcal{S})$	Cardinality of the set $\mathcal{S}$
$\boldsymbol{\Phi} \circ \boldsymbol{\Psi}$	Composition of the transformations $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}$
$\boldsymbol{\Phi}^{-1}$	Inverse of the transformation $\boldsymbol{\Phi}$
δu	Variation of u
Δu	Increment of u
u_0	Initial value of u
u_{ref}	Reference value of u
$u\|_{x=x^*}$	u evaluated at $x = x^*$
$\bar{u}$	Prescribed value of u (Chapter 2, 3)
	Mean value of u (Chapter 4, 6)
$\boldsymbol{u}^{\mathrm{T}}$	Transpose of the vector or tensor $\boldsymbol{u}$
$\mathbf{v}^{-1}$	$:= \mathbf{v}/\\|\mathbf{v}\\|_2^2$, Moore-Penrose inverse of the vector $\mathbf{v}$
$\mathrm{D}u \cdot \boldsymbol{v}$	Directional derivative of u in the direction of the vector $\boldsymbol{v}$
$\partial u/\partial x$	Partial derivative of u with respect to x
$\partial u/\partial t\|_{\boldsymbol{X}}$	Derivative of u with respect to time t, with the material coordinate $\boldsymbol{X}$ held fixed
$\partial u/\partial t\|_{\boldsymbol{\chi}}$	Derivative of u with respect to time t, with the referential coordinate $\boldsymbol{\chi}$ held fixed
$\mathrm{D}u/\mathrm{D}t$	$:= \partial u/\partial t\|_{\boldsymbol{X}}$, material derivative of u
$\dot{u}$	$:= \mathrm{D}u/\mathrm{D}t$
$\ddot{u}$	$:= \mathrm{D}^2 u/\mathrm{D}t^2$
$\mathrm{grad}\, s$	$:= \sum_{i=1}^{d} \partial s/\partial x_i \boldsymbol{e}_i$, gradient of the scalar s
$\mathrm{Grad}\, s$	$:= \mathrm{grad}_{\boldsymbol{X}}\, s$, gradient of the scalar s in the reference configuration
$\mathrm{grad}\, \boldsymbol{v}$	$:= \sum_{i,j=1}^{d} \partial v_j/\partial x_i \boldsymbol{e}_i \otimes \boldsymbol{e}_j$, gradient of the vector $\boldsymbol{v}$
$\mathrm{Grad}\, \boldsymbol{v}$	$:= \mathrm{grad}_{\boldsymbol{X}}\, \boldsymbol{v}$, gradient of the vector $\boldsymbol{v}$ in the reference configuration
$\mathrm{curl}\, \boldsymbol{v}$	$:= \boldsymbol{e}_1(\partial v_3/\partial x_2 - \partial v_2/\partial x_3) + \boldsymbol{e}_2(\partial v_1/\partial x_3 - \partial v_3/\partial x_1) + \boldsymbol{e}_3(\partial v_2/\partial x_1 - \partial v_1/\partial x_2)$, curl of the vector $\boldsymbol{v}$
$\mathrm{div}\, \boldsymbol{v}$	$:= \sum_{i=1}^{d} \partial v_i/\partial x_i$, divergence of the vector $\boldsymbol{v}$
$\mathrm{Div}\, \boldsymbol{v}$	$:= \mathrm{div}_{\boldsymbol{X}}\, \boldsymbol{v}$, divergence of the vector $\boldsymbol{v}$ in the reference configuration

$\operatorname{div}\boldsymbol{T}$	$:= \sum_{i,j=1}^{d} \partial T_{ij}/\partial x_i \boldsymbol{e}_j$, divergence of the tensor $\boldsymbol{T}$
$\operatorname{Div}\boldsymbol{T}$	$:= \operatorname{div}_{\boldsymbol{X}} \boldsymbol{T}$, divergence of the tensor $\boldsymbol{T}$ in the reference configuration
Δs	$:= \operatorname{div}\operatorname{grad} s$, Laplacian of the scalar s
$\boldsymbol{u}\cdot\boldsymbol{v}$	$:= \sum_{i=1}^{d} u_i v_i$, scalar product of the vectors $\boldsymbol{u}$ and $\boldsymbol{v}$
$\boldsymbol{S}\cdot\boldsymbol{T}$	$:= \sum_{i,j=1}^{d} S_{ij} T_{ij}$, scalar product of the second-order tensors $\boldsymbol{S}$ and $\boldsymbol{T}$
$\boldsymbol{v}\cdot\boldsymbol{T}$	$:= \sum_{i,j=1}^{d} v_j T_{ji} \boldsymbol{e}_i$, dot product of the vector $\boldsymbol{v}$ and the second-order tensor $\boldsymbol{S}$
$\boldsymbol{T}\boldsymbol{v}$	$:= \sum_{i,j=1}^{d} T_{ij} v_j \boldsymbol{e}_i$, dot product of the second-order tensor $\boldsymbol{S}$ and the vector $\boldsymbol{v}$
$\boldsymbol{u}\otimes\boldsymbol{v}$	$:= \boldsymbol{u}\boldsymbol{v}^{\mathrm{T}}$, dyadic product of the vectors $\boldsymbol{u}$ and $\boldsymbol{v}$
$\boldsymbol{S}\boldsymbol{T}$	$:= \sum_{i,j,k=1}^{d} S_{ij} T_{jk} \boldsymbol{e}_i \otimes \boldsymbol{e}_k$, tensor product of the second-order tensors $\boldsymbol{S}$ and $\boldsymbol{T}$
$\det\boldsymbol{T}$	Determinant of the tensor $\boldsymbol{T}$
$\operatorname{tr}\boldsymbol{T}$	$:= \sum_{i=1}^{d} T_{ii}$, trace of the tensor $\boldsymbol{T}$
$\lVert\boldsymbol{x}\rVert_p$	$:= \left(\sum_{i=1}^{d} \lvert x_i\rvert^p\right)^{1/p}$, p-norm of the vector $\boldsymbol{x}$
$\boldsymbol{H}^1(\Omega)$	Sobolev space of component-wise weak differentiable functions in $\boldsymbol{L}^2(\Omega)$ with derivatives in $\boldsymbol{L}^2(\Omega)$
$\boldsymbol{H}^1_0(\Omega)$	Set of functions in $\boldsymbol{H}^1(\Omega)$ with vanishing trace on the Dirichlet boundary of Ω
$\boldsymbol{L}^2(\Omega)$	Hilbert space of component-wise Lebesgue-measurable functions with integrable squares over Ω
$\boldsymbol{0}$	Zero vector
a	Axis
$\boldsymbol{a}$	Acceleration vector
$\mathrm{d}a$	Area element in the current configuration
$\mathrm{d}\boldsymbol{a}$	$:= \boldsymbol{n}\mathrm{d}a$, directed area element in the current configuration
A_k	Influence coefficient
$\mathrm{d}A$	Area element in the reference configuration
$\mathrm{d}\boldsymbol{A}$	$:= \boldsymbol{N}\mathrm{d}A$, directed area element in the reference configuration
$\mathcal{A}$	Convergence acceleration scheme
$\boldsymbol{b}$	Body force vector
B_k	Influence coefficient
$\mathcal{B}$	Set of bounding boxes
$\boldsymbol{B}$	$:= \boldsymbol{F}\boldsymbol{F}^{\mathrm{T}}$, left Cauchy-Green deformation tensor
$\hat{\boldsymbol{B}}$	$:= J^{2/3}\boldsymbol{I}$, dilatational (i.e., volume-changing or volumetric) part of the left Cauchy-Green deformation tensor $\boldsymbol{B}$
$\bar{\boldsymbol{B}}$	$:= J^{-2/3}\boldsymbol{B}$, distortional (i.e., volume-preserving or isochoric) part of the left Cauchy-Green deformation tensor $\boldsymbol{B}$
c	Speed of sound (Chapter 2)
	Damping constant (Chapter 4, 5)
c_p	Specific heat capacity
C	Child of a tree node (Chapter 4)
	Center of gravity (Chapter 6, 7)
C_k	Influence coefficient
$\boldsymbol{C}$	$:= \boldsymbol{F}^{\mathrm{T}}\boldsymbol{F}$, right Cauchy-Green deformation tensor

$\hat{\boldsymbol{C}}$	$:= J^{2/3}\boldsymbol{I}$, dilatational (i.e, volume-changing or volumetric) part of the right Cauchy-Green deformation tensor $\boldsymbol{C}$
$\bar{\boldsymbol{C}}$	$:= J^{-2/3}\boldsymbol{C}$, distortional (i.e., volume-preserving or isochoric) part of the right Cauchy-Green deformation tensor $\boldsymbol{C}$
$\boldsymbol{\mathcal{C}}$	Fourth-order material tensor
$\mathbf{C}$	Damping matrix
d	Dimension of space (Chapter 3)
	Distance (Chapter 4, 5)
$\boldsymbol{d}$	Displacement vector
$\mathbf{d}$	Discrete displacement vector
D	Diameter
$\boldsymbol{D}$	Rate-of-strain tensor
e	Error
$\boldsymbol{e}$	Cartesian basis vector
E	Young's modulus
$\boldsymbol{E}$	Green-Lagrange strain tensor
f	Generic function
$\boldsymbol{f}$	External force vector
$\mathbf{f}$	Discrete external force vector
F	External force
$\boldsymbol{F}$	Deformation gradient (Chapter 3)
	Distance function (Chapter 4)
$\hat{\boldsymbol{F}}$	$:= J^{1/3}\boldsymbol{I}$, dilatational (i.e, volume-changing or volumetric) part of the deformation gradient $\boldsymbol{F}$
$\bar{\boldsymbol{F}}$	$:= J^{-1/3}\boldsymbol{F}$, distortional (i.e., volume-preserving or isochoric) part of the deformation gradient $\boldsymbol{F}$
g	Gravitational acceleration
$\mathbf{g}$	Nonlinear field equation
G	Weak form (Chapter 3)
	Shear modulus (Chapter 6)
h	Height
H	Height
$\boldsymbol{H}$	Displacement gradient
$\mathrm{I}_{\boldsymbol{T}}, \mathrm{II}_{\boldsymbol{T}}, \mathrm{III}_{\boldsymbol{T}}$	Invariants of the second-order tensor $\boldsymbol{T}$
$\mathcal{I}$	Interpolation scheme
$\boldsymbol{I}$	Identity mapping (Chapter 2)
	Second-order identity tensor (Chapter 3)
$\boldsymbol{\mathcal{I}}$	Fourth-order identity tensor
$\mathbf{I}$	Identity matrix
j	Time step
J	$:= \det \boldsymbol{F}$, Jacobian determinant (Chapter 3)
	Advance ratio (Chapter 6)
$\boldsymbol{J}$	Jacobian matrix
$\mathbf{J}$	Discrete Jacobian matrix
k	Spring constant (Section 4.3)
	Iteration (Chapter 4 (except Section 4.3), 5, 6)

	Wave number (Chapter 7)
k_t	Thrust coefficient
k_q	Torque coefficient
K	Bulk modulus
$\mathbf{K}$	Tangent stiffness matrix
$\mathbf{K}_\mathrm{m}$	Material stiffness matrix
$\mathbf{K}_\mathrm{s}$	Initial stress matrix
ℓ	Tree level (Chapter 4)
	Length (Chapter 6)
$\boldsymbol{l}$	Angular momentum
L	Length
m	Number of finite volumes (Section 2.1)
	Number of boundary elements (Section 2.2)
	Number of finite elements (Chapter 3)
	Number of subdomains (Section 4.1, 4.2, Section 5.1)
	Number of query points (Section 4.5, 5.4, 5.5)
	Mass (Section 2.1.2, 3.1.2, 4.3, Chapter 6, 7)
m_s	Number of boundary segments (Chapter 2)
	Number of finite element surfaces (Chapter 3)
$\bar{m}$	Specific mass
$\boldsymbol{m}$	External moment
Ma	Mach number
$\mathbf{M}$	Mass matrix
n	Number of nodes (Chapter 3)
	Number of time steps (Section 4.4)
	Number of source points (Section 4.5)
	Rotational speed (Chapter 6)
	Number of mooring lines (Chapter 7)
$\boldsymbol{n}$	Outer unit normal in the spatial or current configuration
N	Shape function (Chapter 3)
	Tree node (Chapter 4)
$\boldsymbol{N}$	Outer unit normal in the reference configuration (Section 3.1.1, 3.1.2)
	Vector of shape functions (Section 3.1.5)
p	Pressure (Chapter 2, 6, 7)
	Polynomial order (Chapter 4, 6)
$\boldsymbol{p}$	Linear momentum (Chapter 3)
	Source point (Chapter 4, 5)
P	Point
$\mathcal{P}$	Predictor scheme (Section 4.2, 4.4)
	Set of source points (Section 4.5, Chapter 5)
$\boldsymbol{P}$	First Piola-Kirchhoff stress tensor
q	Torque (Section 6.14)
	Heat flux (Section 6.17)
$\boldsymbol{q}$	Query point
$\mathcal{Q}$	Set of query points
r	Radius
$\boldsymbol{r}$	Moment arm

$\mathbf{r}$	Residual or out-of-balance vector
R_φ	Joule heating term
$\mathcal{R}$	Set of nearest neighbor or nearest bounding box candidates
$\boldsymbol{R}$	Rotation tensor
s	Shrink factor (Chapter 4)
	Scaling factor (Chapter 6, 7)
S	Sequence
$\tilde{S}$	Transformed sequence
$\mathcal{S}$	Solver
$\boldsymbol{S}$	Second Piola-Kirchhoff stress tensor
t	Time (except Section 6.14)
	Thrust (Section 6.14)
t'	Ramp time
$\boldsymbol{t}$	Traction
T	Final time
u	Generic scalar-valued quantity
$\boldsymbol{u}$	Generic scalar-, vector-, or tensor-valued quantity
$\mathbf{u}$	Generic discrete quantity
U	Dilatational part of the strain energy density U
$\boldsymbol{U}$	Right stretch tensor
v	Volume in the current configuration (Chapter 3)
	Velocity (Chapter 2, 6, 7)
$\boldsymbol{v}$	Velocity
$\hat{\boldsymbol{v}}$	Mesh velocity
$\tilde{\boldsymbol{v}}$	$:= \boldsymbol{v} - \hat{\boldsymbol{v}}$, convective velocity
V	Volume in the reference configuration
$\boldsymbol{V}$	Left stretch tensor
w	Interpolation weight
$\boldsymbol{w}$	Material velocity in the referential configuration
W	Strain energy density (Section 3.1.3)
	Virtual work (Section 3.1.4)
	Width (Chapter 6, 7)
$\bar{W}$	Distortional part of the strain energy density W
$\mathcal{W}$	Set of interpolation weights
$\mathbf{W}$	Interpolation matrix
$\boldsymbol{x}$	Particle in the spatial or current configuration
$\boldsymbol{x}'$	Collocation point
$\boldsymbol{X}$	Particle in the material or reference configuration
$\boldsymbol{y}$	State vector
α	Angle of attack
α_ϑ	Thermal expansion coefficient
α_φ	Linear temperature coefficient
β	Newmark parameter
γ	Diffusion coefficient (Chapter 2)
	Newmark parameter (Chapter 3, 6, 7)

	Peak enhancement factor (Chapter 7)
$\varGamma$	$:= \partial\varOmega$, boundary of the domain $\varOmega$
Δ	Thickness (Chapter 6)
	Draft (Chapter 7)
ε	Tolerance (except Section 6.17)
	Emissivity (Section 6.17)
$\boldsymbol{\varepsilon}$	Linear strain
ζ	Wave elevation
η_0	Efficiency
$\boldsymbol{\eta}$	Test function
$\pmb{\upeta}$	Discrete test function vector
θ	Angle between cell normals (Chapter 4)
	Misalignment angle θ (Chapter 7)
ϑ	Temperature
$\boldsymbol{\varTheta}$	Inertia tensor in the inertial frame
$\hat{\boldsymbol{\varTheta}}$	Inertia tensor in the body frame
λ_ϑ	Thermal conductivity
λ_φ	Electrical conductivity
$\boldsymbol{\lambda}$	Weighting vector
μ	Dynamic viscosity (Section 2.1, Chapter 6)
	Doublet strength (Section 2.2)
ν	Kinematic viscosity
$\xi, \boldsymbol{\xi}$	Coordinate in the parameter space of a finite element
ρ	Density
ρ_∞	Spectral radius
$\boldsymbol{\rho}$	Quaternion
σ	Source strength
σ_{sb}	Stefan-Boltzmann constant
σ_{v}	von Mises stress
$\boldsymbol{\sigma}$	Cauchy stress
ϕ	Generic scalar quantity (Chapter 2)
	Electric potential (Chapter 6)
	Phase angle (Chapter 7)
$\boldsymbol{\varphi}$	$:= \boldsymbol{\varPhi} \circ \boldsymbol{\varPsi}^{-1}$, bijective transformation from the material or reference configuration $\varOmega_{\boldsymbol{X}}$ to the spatial or current configuration $\varOmega_{\boldsymbol{x}}$ (Chapter 2, 3)
	Vector storing rotations about x, y, and z (Chapter 4)
$\varPhi$	Generic extensive property (Section 2.1)
	Velocity potential (Section 2.2)
$\boldsymbol{\varPhi}$	Bijective transformation from the referential configuration $\varOmega_{\boldsymbol{\chi}}$ to the spatial configuration $\varOmega_{\boldsymbol{x}}$
$\boldsymbol{\chi}$	Particle in the reference configuration
$\boldsymbol{\varPsi}$	Bijective transformation from the referential to the material configuration
ω	Relaxation factor (Chapter 4, 6)
	Angular frequency (Chapter 6, 7)
$\boldsymbol{\omega}$	Angular velocity pseudo-vector
$\varOmega$	$\subset \mathbb{R}^d$, domain in d-dimensional space $\mathbb{R}^d$

$\partial\Omega$	$\subset \mathbb{R}^{d-1}$, boundary of the domain $\Omega \subset \mathbb{R}^d$ in d-dimensional space $\mathbb{R}^d$

Abstract

A broad range of engineering applications are governed by coupled multifield phenomena. Due to their highly nonlinear nature, fluid-structure interaction problems belong to the most challenging problems in this area. Prominent examples for such problems can, in particular, be found in the maritime industry. In this thesis, emphasis is placed on the numerical investigation of the fluid-structure interaction of a floating offshore wind turbine and of the landing maneuver of a crew transfer vessel to an offshore wind turbine. Due to the ever increasing computational resources, even such highly complex problems have become amenable to a numerical analysis, which helps to provide a deeper insight into the governing physical processes, to reduce the number of expensive experiments, to increase the confidence in the final product, and, last but not least, to reduce costs by shortening the product development cycle.

In the present work, a partitioned solution approach is followed in order to split a coupled problem into separate subproblems, which are coupled by iteratively exchanging the relevant field quantities within a time increment. This procedure enables the use of different spatial and temporal discretization schemes in each of the subdomains. Existing specialized and efficient solvers can then be reused to solve the subproblems – which significantly enhances modularity, software reusability, and also performance. However, these advantages come at the expense of reduced stability of the solution process. Appropriate measures must hence be taken to circumvent stability problems and to accelerate the convergence of the partitioned solution procedure. Therefore, different predictors are proposed so as to provide a reasonable initial guess for the solution in the current time increment and to help to reduce the number of implicit iterations. Regarding the transfer of the relevant field quantities between possibly non-conforming discretizations, several mesh-independent and mesh-dependent interpolation schemes are presented and assessed with respect to accuracy and computational efficiency. Moreover, efficient convergence acceleration schemes, which are suitable to stabilize and accelerate the coupling procedure, are discussed in detail.

In order to simplify the computer implementation of customized coupling strategies for various kinds of multifield problems, the C++ software library *comana* is presented. It offers a vast range of modular and well-tested algorithmic building blocks, which can easily be combined to create a coupling algorithm tailored to the specific problem under consideration. Based on a master/slave architecture, *comana* allows the user to select from plenty of solvers for different physical phenomena and to simply exchange them in a black-box manner. Shared- and distributed-memory parallelized solvers can be integrated into a coupled computation without difficulty rendering even large computations possible. Preparing a solver for a coupled simulation only requires an adapter module and very little modifications in the solver code. Adapters for various solvers for thermodynamics, fluid and structural dynamics are readily provided; adapters not yet available can be implemented with little effort.

In the last part of this work, the software library is verified by means of numerous benchmark problems – and it is also applied to several advanced applications from the maritime industry. Exploiting the full versatility of the software library *comana*, it is demonstrated that the partitioned solution approach is well suited to solve even highly complex and strongly coupled problems efficiently. Particular focus is placed on the fluid-structure interaction of a floating offshore wind turbine and on the landing maneuver of a service ship to an offshore wind turbine, as specific applications from the maritime industry.