

STABLE AND CONSERVATIVE NUMERICAL SCHEMES
FOR HYPERBOLIC PROBLEMS USING NON-CONVEX
POLYGONAL MESHES

Dissertation
zur
Erlangung der naturwissenschaftlichen Doktorwürde (Dr. sc. nat.)
vorgelegt der
Mathematisch-naturwissenschaftlichen Fakultät
der
Universität Zürich
von
Élise Le Méledo
aus Frankreich

Promotionskommission

Prof. Dr. Rémi Abgrall (Vorsitz und Leiter der Dissertation)
Prof. Dr. Stefan Sauter
Prof. Dr. Jean Bertoin

Zürich, 2022

Table of Contents

1	Introduction	3
1.1	Problem of interest and general difficulties	3
1.2	Scope of the presented work	5
1.3	Thesis contribution	6
1.4	Outline	8
2	Preliminaries	9
2.1	Considered type of problems	11
2.1.1	Conservation principle	12
2.1.2	A founding example	20
2.1.3	Hyperbolicity and discontinuity propagation	27
2.1.4	Weak solutions	28
2.1.5	Solution profiles	29
2.1.6	Entropy solutions	36
2.2	A brief algebraic toolbox	39
2.2.1	Multivariate polynomial spaces	39
2.2.2	Polynomial representation and degrees of freedom	41
2.2.3	Basis tuning on degrees of freedom	44
2.2.4	Basis functions adjustment to geometry distortion	46
2.3	A brief numerical analysis toolbox	50
2.3.1	Basic concepts of discretisation	50
2.3.2	Essential properties of a numerical scheme	55
2.4	Some classical numerical schemes	58
2.4.1	Discontinuous Galerkin methods	58
2.4.2	Flux reconstruction schemes	60
2.4.3	Residual distribution framework	74
2.4.4	Methods strengths and drawbacks	81
2.5	An entropy conservative scheme	83
2.5.1	Reformulation of a Flux Reconstruction scheme	83
2.5.2	Discrete conservation of the recast scheme	85
2.5.3	Entropy conservation of the recast scheme	86
2.5.4	Flux Reconstruction nature of the corrected recast scheme	90
2.5.5	Summary of the construction	93
2.5.6	Conclusion and perspectives	94

3	$H(\text{div})$-conforming elements on general polytopal meshes	97
3.1	Conforming discretisation strategies	99
3.1.1	Discrete features and conformity	100
3.1.2	The variational space $H(\text{div})$ and its specificities	101
3.1.3	Application of $H(\text{div})$ -conforming discretisations	102
3.1.4	Classical polytopal and $H(\text{div})$ -conforming elements	104
3.1.5	Scope of the presented method	105
3.2	Description of two conforming elements	107
3.2.1	Simplicial Raviart – Thomas elements	107
3.2.2	Quadrilateral Raviart – Thomas elements	115
3.2.3	The classical Virtual Elements	117
3.2.4	The $H(\text{div})$ -conforming virtual element space	119
3.3	A framework for arbitrary polytopes	121
3.3.1	The general idea in a nutshell	122
3.3.2	Necessary conditions over spaces and elements	122
3.3.3	A class of admissible approximation spaces	123
3.3.4	Definition of $H(\text{div})$ -conforming elements	129
3.3.5	Summary of the construction	146
3.3.6	Two examples in two dimensions	148
3.3.7	Link to other discretisation spaces	151
3.3.8	Numerical results	154
3.3.9	Critical assessment of the proposed approach	158
4	A conservative and continuity preserving interface correction	161
4.1	Problem statement, modelling, and approximation strategy	163
4.1.1	Modelling strategy	164
4.1.2	Conservation principle	168
4.1.3	Dedicated approaches and numerical schemes	171
4.1.4	Scope of the presented approach	176
4.2	Description of three fundamental methods	177
4.2.1	The Level Set approach	177
4.2.2	The Volume of Fluid method	179
4.2.3	The <i>THINC-LS</i> approach	181
4.3	A continuity preserving procedure	184
4.3.1	The general idea in a nutshell	184
4.3.2	An intuitive continuous interface correction	185
4.3.3	Extensions	197
4.3.4	Numerical approximations	209
4.3.5	Numerical results	216
4.3.6	Critical assessment of the proposed approach	225

List of figures

2.1	Problem definition: spatial and variational domains	11
2.2	Local conservation principle: contributions diagram	12
2.3	Local conservation principle: global dynamic contextualisation .	12
2.4	Motion and transport: illustration of displacement and distortion	13
2.5	Motion and transport: illustration of the transport theorem . .	15
2.6	Solution profiles: discontinuity creation	28
2.7	Solution profiles: discontinuity decomposition	30
2.8	Solution profiles: physical and unphysical solutions	33
2.9	Solution profiles: non-uniqueness of entropy solutions	34
2.10	Solution profiles: one-dimensional Euler equations	35
2.11	Solution profiles: general notion of entropy	36
2.12	Algebra toolbox: duality relationship with a set of basis functions	44
2.13	Algebra toolbox: orientation-preserving mapping	48
2.14	Algebra toolbox: orientation-preservation and non-convexity . .	49
2.15	Numerical analysis toolbox: representation of a discrete solution	50
2.16	Numerical analysis toolbox: unstructured spatial discretisation	52
2.17	Numerical analysis toolbox: possible mesh pathologies	53
2.18	Numerical analysis toolbox: convergence property	55
2.19	Numerical analysis toolbox: illustration of the stability property	56
2.20	Flux Reconstruction: update procedure I/II	64
2.21	Flux Reconstruction: choice of lifting functions	71
2.22	Flux Reconstruction: towards a geometrical flexibility	72
2.23	Flux Reconstruction: update procedure II/II	73
2.24	Residual Distribution: scheme construction, from primal to dual	76
2.25	Residual Distribution: geometrical and variational mesh duals	76
3.1	Raviart – Thomas elements: simplicial case representation . . .	114
3.2	Raviart – Thomas elements: quadrilateral case representation .	116
3.3	Virtual elements framework: conforming layout	120
3.4	Unisolvence: normal determination matrix	141
3.5	Unisolvence: internal determination matrix	144
3.6	Conforming example: adaptivity towards the order and geometry	149
3.7	Numerical results: normal component of internal basis functions	154
3.8	Numerical results: normal components of normal basis functions	155

3.9 Numerical results: behaviour of degenerating basis functions	155
3.10 Numerical results: basis function scaling	156
3.11 Numerical results: degeneracy of basis functions	157
3.12 Numerical results: investigation of the reduced setting	157
4.1 Problem definition: domain, phases and interface	163
4.2 Modelling strategy: prominent flow behaviours in horizontal pipes	164
4.3 Modelling strategy: depiction of two-phase flows modellings . .	165
4.4 Modelling strategy: update of the time-discretised model	166
4.5 Modelling strategy: example of interface topological changes . .	167
4.6 Conservation principle: two-phase mass conservation principle	168
4.7 Conservation principle: two-phase discrete conservation principle	169
4.8 Conservation principle: approximation within a control volume	170
4.9 Conservation principle: impact of the quadrature points	170
4.10 Level Set method: definition of an implicit interface	177
4.11 Level Set method: development of singularities	178
4.12 Level Set method: numerical issues with perturbed function . .	179
4.13 Volume of Fluid method: mixture and interface definition	179
4.14 Volume of Fluid method: interfacial cells and mixture definition	180
4.15 Volume of Fluid method: interface evolution	180
4.16 THINC approach: semisequential update chart	181
4.17 Intuitive interface correction: spatial layout	185
4.18 Intuitive interface correction: continuity-preserving correction .	188
4.19 Extensions: need of continuous mapping in non-convex cells .	197
4.20 Extensions: continuous mapping of a non-convex cell	198
4.21 Extensions: convex polygons of reference	198
4.22 Extensions: spatial layout of a staggered setting	202
4.23 Extensions: correction procedure in a staggered setting	204
4.24 Extensions: interface layouts yielding a same volume fraction .	208
4.25 Numerical approximations: composite quadrature scheme	209
4.26 Numerical approximations: volume of fluid estimator	215
4.27 Numerical approximations: smooth bijective map	216
4.28 Numerical results: corrected interface layouts	217
4.29 Numerical results: corrected multi-component interface layouts	218
4.30 Numerical results: behaviour of the volume of fluid estimator I/II	219
4.31 Numerical results: behaviour of the volume of fluid estimator II/II	220
4.32 Numerical results: continuity-preserving correction	221
4.33 Numerical results: impact of the locator function shape I/IV .	222
4.34 Numerical results: impact of the locator function shape II/IV .	222
4.35 Numerical results: impact of the locator function shape III/IV .	223
4.36 Numerical results: impact of the locator function shape IV/IV .	223
4.37 Numerical results: limitations of the proposed approach	224

List of tables

3.1	$H(\text{div})$ -conforming examples: normal degrees of freedom	147
3.2	$H(\text{div})$ -conforming examples: 2D normal degrees of freedom . . .	148
3.3	$H(\text{div})$ -conforming examples: reduced setting	150
4.1	Numerical approximations: face parametrisation's derivatives .	212