Flexible-Membrane FSI Solver

Rigid-Body Frame + Elastic Membrane Panels — Single-Phase Standard Solver with Optional Two-Phase VoF Add-On

Technical Description for Customer Proposals

1 Executive Summary

This document describes a computational fluid–structure interaction (FSI) solver that couples a three-dimensional incompressible CFD solver with a rigid-body dynamics model and a nonlinear thin-membrane finite-element model. The solver is designed to predict the coupled motion of frame structures equipped with flexible membrane panels under aerodynamic or hydrodynamic loading.

The standard solver dhcae_membraneFsiFoam covers single-phase incompressible flow (air or single-fluid water). For applications involving a free water surface or two-phase mixtures, an optional Volume-of-Fluid (VoF) add-on provides three additional solver variants that share the same FSI core library (libdhcaeMembraneFsi.so):

- dhcae_membraneFsiInterFoam — two-phase incompressible (isoAdvector, sharp interface).
- dhcae_membraneFsiCompInterIsoFoam — two-phase compressible (isoAdvector, with compressible fluid formulation, e.g. perfectFluid).
- dhcae_membraneFsiCompInterFoam — two-phase compressible (MULES, more diffusive but more robust).

Key distinguishing features (shared by all variants):

- Combined rigid-body + flexible-membrane kinematics within a single mesh-motion framework.
- Total-Lagrangian membrane FEM with geometric nonlinearity, full bilinear Quad elements (2×2 Gauss) or CST triangles.
- Multi-body kinematic trees: a single membrane patch can be associated with multiple parent rigid bodies via the parentBodyPatches list (e.g. double-pendulum configurations).
- Implicit (Gauss–Seidel) FSI coupling with Aitken-Δ^2 fixed-point relaxation. IQN-ILS quasi-Newton acceleration with preCICE-style safety nets is available as an alternative.
- Robust force handling: spatial pNet smoothing, optional temporal low-pass (IIR) filter, force under-relaxation, pre-stress (T0) and reference-pressure offset (pOffset).

- Tension-field wrinkling model for physically correct membrane response near the onset of compressive stresses.
- Jacobi mesh smoothing to maintain mesh quality under large structural deflections.
- Optional pre-settle / wave-develop workflow for water-FSI cases: the body and free surface reach hydrostatic equilibrium under strong damping before any transient excitation is applied.
- Parallel execution (MPI) with demonstrated near-linear scaling.

2 Physical Problem and Application Areas

The solver addresses engineering problems where a lightweight elastic membrane, mounted in a rigid or spring-supported frame, deforms under fluid loading. Typical applications:

- Aerodynamic membranes and flexible screens in wind engineering (single-phase air).
- Fluid-loaded diaphragms and valves in hydraulic or HVAC systems (single-phase water).
- Sail-like structures in naval or wind-energy applications.
- Submerged flexible enclosures and aquaculture pens under wave loading (two-phase VoF add-on).
- Biological and medical flow devices (flexible walls in channel flow).

The characteristic feature of this class of problems is the two-way coupling: the fluid pressure deforms the membrane, which in turn alters the flow field — and, in two-phase cases, the free surface. Large deflections (of the order of the membrane span) are physically admissible and must be handled with geometric nonlinearity.

3 Dynamic Mesh: Morphing Approach

All solver variants use mesh morphing (Arbitrary Lagrangian–Eulerian, ALE) to track the moving structure within a fixed topological mesh. No remeshing is required during the simulation. The mesh deforms continuously to follow the structure, preserving all boundary patch identities and inter-processor communication.

3.1 Hierarchical Motion Model

The overall mesh displacement is decomposed into hierarchically coupled parts:

- Rigid-body motion of one or several frame structures (translations, rotations, joints, springs, dampers).
- Elastic deformation of the membrane panels relative to the moving parent body (or, optionally, to a kinematic blend of multiple parent bodies).

This decomposition ensures continuity of mesh displacement at the frame–membrane boundary: membrane node displacements are written as the sum of the parent-body translation and the FEM deformation, so no spurious gaps or overlaps arise at the junction.

For multi-body configurations, each membrane patch is associated with one or more parent bodies via a parentBodyPatches list; the kinematic frame transformation is taken from the body whose patches define that membrane region.

3.2 Rigid-Body Motion Component

Frame dynamics is solved by Newmark time integration of the Newton–Euler equations. The implementation extends the standard OpenFOAM rigid-body mesh-motion library:

- Arbitrary multi-body kinematic trees (joints: translation, rotation, composite).
- Spring, damper, and gravity restraints; additional linearDamper restraints for added-mass-dominated cases.
- Distance-weighted interpolation of frame motion to interior mesh points.
- accelerationRelaxation and accelerationDamping for numerical scaling of body response (useful for very strong added-mass coupling, and for the body-freeze phase of the wave-develop workflow).

Because the flexible-membrane solver is a strict extension of the rigid-body library, all pure rigid-body cases run without modification by simply omitting the flexible-body sub-dictionary.

3.3 Membrane Mesh-Motion Component

After the frame displacement is computed, the deformed membrane surface is used as a Dirichlet boundary condition for the interior mesh. A Jacobi point-Laplacian smoother propagates this surface displacement smoothly into the volume mesh:

- All boundary-patch nodes (frame, membrane, channel walls) are fixed to their prescribed positions.
- All interior mesh nodes are iteratively averaged over their topological neighbours (50 Jacobi sweeps by default).
- The smoother prevents cell inversion even when the membrane deflection exceeds the local cell thickness.

4 Structural Model: Nonlinear Membrane FEM

4.1 Formulation

Each membrane panel is modelled as a geometrically nonlinear thin membrane (zero bending stiffness) using the Total-Lagrangian formulation. Key ingredients:

- Green–Lagrange strain tensor — exact for arbitrarily large deflections.
- 2nd Piola–Kirchhoff stress — work-conjugate to the Green–Lagrange strain.
- St. Venant–Kirchhoff constitutive law (isotropic, plane-stress): Young's modulus E, Poisson's ratio ν.
- Quad elements (bilinear shape functions, 2×2 Gauss integration) — recommended for structured Hex meshes; eliminates checkerboarding caused by triangle diagonal split.

- CST triangles available for unstructured surface meshes and as fallback for mixed Hex/Tet meshes (per-face).
- Optional initial pre-stress T0 (in N/m) and reference pressure offset pOffset for membranes with controlled internal pressure (e.g. submerged closed enclosures).
- Lumped-area nodal load assembly for the fluid pressure load, with parallel-safe globalIndex assembly across processor boundaries.

4.2 Newton–Raphson Solver

The static equilibrium equation is solved by Newton–Raphson iteration with a diagonal (lumped) stiffness matrix. Each NR iteration:

- Assembles the residual force vector (internal elastic forces – external pressure load).
- Assembles the diagonal tangent stiffness.
- Updates nodal displacements: $\Delta u = K\_diag^{-1} \cdot R$.
- Applies a bidirectional displacement bow-limiter based on a maximum mesh-velocity criterion to prevent over-shooting in both directions.

Convergence is declared when the relative residual norm falls below the user-specified tolerance (default 10^{-4}). Typical convergence requires 5–30 NR iterations per FSI sub-step.

4.3 Tension-Field Wrinkling Model

For membranes operating near or beyond the onset of compressive in-plane stresses, a tension-field wrinkling correction is available. The model modifies the stress state to enforce non-negative principal stresses, replacing the physically inadmissible compressive region with a slack-membrane (zero-stress) state. This prevents numerical locking and yields physically correct deflection shapes for highly loaded or large-deflection cases.

4.4 Boundary Conditions and Coupling to the Frame

At the membrane boundary (junction with the rigid frame or cross-beam), nodal displacements are prescribed to be zero relative to the parent frame — corresponding to a fully clamped edge. Additional features:

- Optional edge-spring and edge-beam reinforcements model flexible or tensioned edges.
- constrainToNormal flag restricts membrane motion to the surface normal (useful when modelling cantilever-like sub-segments).
- Per-node sign correction for pOffset based on a user-supplied insidePoint geometry, with optional pOffsetRampTime for smooth initialisation.
- Multi-parent-body coupling via parentBodyPatches: kinematic frame at each node is taken from the closest body, enabling configurations like membranes spanning two independently moving rigid frames.

5 FSI Coupling Architecture

5.1 Implicit Gauss–Seidel Outer Loop

The FSI coupling uses an implicit, partitioned Gauss–Seidel ("strong coupling") strategy. The structural problem is solved before the fluid problem within each FSI iteration:

- 1. Update the structure on the current mesh: rigid-body Newmark step (once per time step) + membrane FEM Newton–Raphson, using the current fluid pressure.
- 2. Apply Aitken-Δ^2 or IQN-ILS relaxation to the displacement update.
- 3. Update the mesh (Jacobi point smoothing applied to the new structural boundary).
- 4. Solve the CFD pressure–velocity system (PIMPLE inner loop) on the new mesh.
- 5. Check FSI convergence: max(displacement residual, force residual) < tolerance.
- 6. If converged advance to next time step; otherwise repeat from step 1.

Solving the structure first ensures that the membrane responds to the pressure of the current iterate consistently with the deformed mesh on which the next CFD update is built. This guarantees that fluid and structural solutions are mutually consistent at every time step, in contrast to explicit staggered approaches which are only first-order accurate in time.

5.2 Aitken-Δ^2 Relaxation

Partitioned implicit FSI without relaxation typically diverges or converges slowly for problems with light structures and strong added-mass effects. The Aitken-Δ^2 method adapts the relaxation factor ω automatically from the displacement residuals of successive FSI iterations. ω is clamped to [ωmin, 1] with a user-defined starting value. In practice, most time steps converge in 1–5 FSI iterations.

5.3 IQN-ILS Quasi-Newton Coupling (Optional)

For strongly coupled added-mass-dominated cases (lightweight structure in dense fluid, e.g. lid-driven-cavity-style benchmarks), an IQN-ILS (Interface Quasi-Newton with Inverse Least-Squares Jacobian) accelerator is available as an alternative to Aitken. The implementation includes the preCICE-style safety nets:

- QR filtering of the residual history with adaptive column dropping when conditioning degrades.
- Step-size limiter that triggers Aitken fallback if the quasi-Newton update is unphysically large.
- History reset across time steps (iqnReuseCols = 0 is the recommended default; reuse can re-introduce instability).

IQN-ILS is enabled by setting iqnMaxCols > 0 in the solver configuration. For more common, weakly coupled cases (gas–fluid, water with lightly loaded membranes), pure Aitken remains the recommended default — fewer parameters to tune and often comparable convergence.

5.4 Force Filtering and Relaxation

In addition to displacement-side relaxation, the FSI loop offers force-side stabilisation mechanisms to suppress numerical pressure spikes from the moving mesh:

- forceOmega — under-relaxation factor applied to the pNet load between successive FSI iterations.
- pNetFilterTau — exponential moving-average (IIR) low-pass filter on the membrane load, applied once per time step (not per FSI iteration). Suppresses high-frequency content while preserving the physical pressure field used in the CFD.
- pNetSmoothIter — spatial Laplacian smoothing of pNet on the membrane surface; useful at multi-block joints with discontinuous mesh resolution.

5.5 FSI Ramp and Start-Time Control

Two optional parameters smooth the start of the structural response:

- fsiStartTime — mesh frozen and structure rigid until this physical time. Useful for letting the flow reach a quasi-steady state.
- fsiRampTime — after FSI is activated, the structural load is ramped from 0 to 100 % over this duration. Prevents impulsive deflections at start-up.

For wave-impact cases, a body-freeze phase via accelerationDamping = 0 is also available: the body is held in place while the wave propagates and the pressure field develops; the body is then released to interact with the established wave field. This pattern mirrors the floatingObject tutorial in standard OpenFOAM.

6 Solver Variants — Standard + VoF Add-On

6.1 Standard Solver — dhcae_membraneFsiFoam

The standard solver covers single-phase incompressible flow and is the most thoroughly validated variant. It is built on the pimpleFoam framework and shares the FSI core library libdhcaeMembraneFsi.so with the VoF add-on solvers.

- Use case: air around membranes, single-fluid water, generic incompressible flows.
- Time-step regime: typical dt = 0.5–5 ms depending on mesh and characteristic velocity.
- Optional artCompressibility for fast pressure-equation convergence on moving meshes.

6.2 Two-Phase VoF Add-On

For free-surface and two-phase applications (wave–body interaction, partial submergence, sloshing), three additional solver variants are available. All link the same FSI core library; only the fluid sub-module differs. Cases set up for the standard solver translate to the VoF add-on by adding an alpha.water field and a setFieldsDict.

Solver dhcae_	Fluid model	Use case	Typical dt
membraneFsiInterFoam	interIsoFoam basis, incompressible two-phase, isoAdvector (sharp α-front)	Free-surface wave on body, water-FSI without acoustic effects	0.2–1 ms
membraneFsiCompInterIsoFoam	compressibleInterIsoFoam basis, perfectFluid water (K = 2.2 GPa) + perfectGas air	Realistic water compressibility, acoustic damping of pressure spikes	0.1–0.3 ms
membraneFsiCompInterFoam	compressibleInterFoam basis, MULES α-advection	Robust fallback when isoAdvector α-bounds become marginal	0.1–0.3 ms

For wave-on-body simulations, a two-phase or three-phase Allrun workflow is provided that splits the simulation into:

- Phase 1 (settle): no wave, strong damping, large time step — body and membrane reach hydrostatic equilibrium.
- Optional Phase 2 (wave-develop, body frozen): the wave is applied via setFields while accelerationDamping = 0 keeps the body in place, so the pressure field develops before any body response.
- Phase 3 (wave): the body is released with reduced damping and responds to the fully developed wave.

7 Computational Performance

7.1 Implicit vs. Explicit Coupling — Benchmark (Single-Phase)

The implicit single-phase solver was benchmarked against an explicit (staggered) version on a 3-D channel-flow case with two elastic membrane panels (2 × 1.24 m^2) in a spring-mounted rigid frame. Both used identical meshes and time steps.

Metric	Explicit Staggered	Implicit (this solver)	Improvement
Simulation duration	6 s physical	6 s physical	—
Wall-clock (6 cores)	1658 s	964 s	× 1.72 faster
PIMPLE outer iters	90 000	16 037	× 5.6 fewer
FSI iters / step (avg)	15 (fixed)	1.28 (adaptive)	× 11.7 fewer
Frame disp. (t=6 s)	578.0 mm	579.7 mm	0.13 % diff.

The 1.72× wall-clock speed-up arises from (i) fewer PIMPLE outer iterations per time step in the converged steady state, and (ii) the adaptive FSI iteration count via Aitken.

7.2 Parallel Scaling

All solver variants use MPI domain decomposition. The decomposition preserves baffle face-pairs on the same processor (preserveBaffles constraint) and keeps the membrane patches on a single processor (singleProcessorFaceSets constraint) to avoid inter-processor communication in the FEM solve. All FSI-coupling operations (Aitken or IQN-ILS, FEM solve, Jacobi smoothing) use correct MPI collective semantics. Typical parallel efficiency is >85 % for 4–16 cores on the benchmark geometry. Scotch decomposition is robust for ≥ 16 cores; for smaller core counts (≤ 12), hierarchical decomposition with an explicit n-vector is recommended to avoid degenerate partitions.

8 Key Solver Parameters

All parameters are specified in solver configuration dictionaries. No source-code modification is required for a new case. The most important parameters are grouped below.

8.1 FSI Coupling Parameters (dynamicMeshDict)

Parameter	Default	Description
rhoFluid	1.225 kg/m^3	Reference fluid density (1 for VoF; pNet already in Pa)
pClamp	200 m^2/s^2	Maximum |p/ρ| before clamping (NR safety)
maxMeshVelocity	0.5 m/s	Body-translation rate limit per FSI iteration
maxDeltaDispFrac	0.002	Bow-limiter as fraction of characteristic length
fsiStartTime	0 s	Physical time before which FSI is frozen
fsiRampTime	0.1 s	Duration of linear load ramp after activation
omegaInit / omegaMin	0.1 / 0.05	Aitken relaxation factor initial value and lower bound
iqnMaxCols / iqnReuseCols	0 / 0	IQN-ILS columns (0 = pure Aitken)
forceOmega	0.5–1.0	pNet under-relaxation between FSI iterations
pNetFilterTau	0–0.1 s	Temporal IIR low-pass on pNet (0 = off)
pNetSmoothIter	2–10	Spatial Laplacian smoothing iterations on pNet
wrinklingModel	none / tensionField	Wrinkling correction
pOffset, pOffsetInsidePoint, pOffsetRampTime	0 / — / 0.1 s	Reference internal-pressure offset and its ramp
accelerationRelaxation, accelerationDamping	0.5 / 1.0	Numerical scaling of body response (set accelerationDamping = 0 to freeze body during wave-develop phase)

8.2 Membrane Parameters (flexibleBodies sub-dict)

Parameter	Unit	Description
thickness	m	Membrane thickness h
E, nu, rho	Pa, –, kg/m^3	Young's modulus, Poisson's ratio, density
T0	N/m	Initial pre-stress (distinct from pOffset, which is a fluid-side reference)
rayleighAlpha, rayleighBeta	1/s, s	Rayleigh damping coefficients
cornerSpringK, edgeBeamEA, edgeSpringK, rimSpringK	N/m, N, N/m, N/m	Optional edge/corner reinforcements
constrainToNormal	bool	Restrict displacement to surface normal
masterPatch, slavePatch, parentBodyPatch(es)	patch names	Membrane patch identification and parent-body coupling (list for multi-body)

8.3 Solution Parameters (fvSolution PIMPLE)

Parameter	Typical	Role
maxFsiIter	15–30	Max FSI Gauss–Seidel iterations per time step
minFsiIter	3–5	Minimum FSI iterations (forces convergence-quality check)
fsiTol	0.001–0.005	Tolerance on max(disp residual, force residual)
nOuterCorrectors	3	PIMPLE outer iterations per FSI sub-step (≥ 2 required)
nCorrectors	2	SIMPLE pressure correctors inside PIMPLE outer
nNonOrthogonalCorrectors	1–3	Non-orthogonal correctors; raise for large deflections
moveMeshOuterCorrectors	yes	Required true for implicit FSI
residualControl (U, p)	1e-4	Early-exit thresholds for PIMPLE
artCompressibility (single-phase only)	0 – 4e-4 s^2/m^2	Pseudo-compressibility for transient pressure on a moving mesh (single-phase solver only)

9 Software Architecture

9.1 Modular Design

The suite is structured into modules that are independently testable:

- Membrane body module — FEM data, NR solver, stress/strain output, wrinkling logic, edge/corner reinforcements, pOffset handling. Multiple panels supported simultaneously.
- Rigid-body flexible mesh-motion module — orchestrates the FSI outer loop, Aitken / IQN-ILS relaxation, force filtering, and Jacobi smoothing. Extends the standard rigid-body library without modifying it.
- Mesh-motion boundary condition — applies the computed nodal displacements to both master and slave sides of the membrane baffle.
- Solver executables — one standard solver (dhcae_membraneFsiFoam, single-phase incompressible) plus three VoF variants that share the FSI core via the libdhcaeMembraneFsi.so shared library.

9.2 Compatibility with the Rigid-Body Motion Library

The solver inherits all capabilities of the standard rigid-body dynamics library:

- Full multi-body kinematic tree (composite joints Px / Py / Pz / Rx / Ry / Rz, plus null and prescribed).
- Built-in restraint types: linearSpring, linearDamper, prescribedRotation, plus user-side accelerationDamping and accelerationRelaxation.
- Newmark time integration with user-tunable γ, β.
- Per-body force/moment/displacement/velocity report output.

The flexible-membrane extension is purely additive: a flexibleBodies sub-dictionary is added alongside the existing bodies sub-dictionary. Existing pure rigid-body cases require no modification.

9.3 Output

At every saved time step the solvers write:

- Standard CFD fields: U, p (and p_rgh, alpha.water, T as applicable to the variant).
- Per-membrane structural fields: in-plane strain tensor, 2nd Piola–Kirchhoff stress tensor, principal stresses σ_1, σ_2, von Mises stress, wrinkling state, and displacement magnitude.
- Nodal displacement field (restart support).
- Rigid-body kinematics: position, velocity, acceleration of each body, with on-screen report and per-time-step text logs.
- Optional probes (waveProbes, patchProbes) and exponentially-averaged mean fields (pMean, UMean) for diagnostics.

10 Summary of Capabilities

Feature	Capability
Structural model	Nonlinear membrane FEM, Total-Lagrangian, Quad (full) or CST triangles, large deflections
Rigid-body dynamics	Multi-body tree, springs, dampers, joints, Newmark integration
Multi-body / membrane coupling	parentBodyPatches list: one membrane may bridge multiple rigid bodies (e.g. double-pendulum)
Mesh motion	Morphing (ALE), Jacobi smoothing, no remeshing
FSI coupling	Implicit Gauss–Seidel (structure first, then fluid); Aitken-Δ^2 or IQN-ILS acceleration
Force handling	Spatial pNet smoothing, temporal IIR filter, force under-relaxation, pre-stress T0, pOffset
Wrinkling	Tension-field model ($\sigma_1 \geq 0$ enforcement)
Standard solver	dhcae_membraneFsiFoam — single-phase incompressible
VoF add-on (optional)	Three two-phase variants: incompressible isoAdvector / compressible isoAdvector / compressible MULES
Wave-on-body workflow	Optional pre-settle / wave-develop / wave Allrun pattern with body-freeze phase
Multiple panels	≥ 2 membranes simultaneously (different materials)
Parallel execution	MPI domain decomposition, tested up to 16 cores
Performance vs. explicit	1.7× faster wall-clock (single-phase benchmark)
Output	Full CFD + structural stress/strain fields per time step
Configuration	Single dictionary, no source-code changes for new cases

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