AN INNOVATIVE FLUID-STRUCTURE COMPUTATIONAL FRAMEWORK FOR SUPERSONIC PARACHUTE INFLATION DYNAMICS

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45 years since the 1\textsuperscript{st} known instance of a successful parachute operation in the wake of a blunt object at \textit{supersonic} speeds (NASA, 1972, preparation for the Viking missions to Mars)

Houmard, the Goodyear Aerospace Corporation (1972)

“the stress analysis of the canopy cloth is extremely complicated, since \textit{maximum stresses occur during opening}, which is when the shape and load change rapidly”

- the majority of studies deal “with inflated canopy shapes in which static equilibrium conditions are applied to inflated shapes during intermediate stages of inflation”

Lingard, UK-based Vorticity Ltd. (2010)

- technology no information exists fully explaining parachute behavior in supersonic flow“
Ringsail parachute

- \( D > 30 \text{ m} \): largest supersonic parachute ever tested for landing on Mars (2015)
- failure occurs at a dynamic load that is lower than the static test load
COMPLEX AND CHALLENGING MULTIDISCIPLINARY PROBLEM

- Fluid-Structure Interaction (FSI) problem
  - shocks (Mach 2.5)
  - turbulent wake
  - geometric and material porosities
  - geometric and material nonlinearities
  - massive self-contact
  - material failure

  **highly nonlinear FSI problem**

- Embedded (immersed) Boundary Method (EBM) for CFD and FSI
Enhanced FIVER method (Finite Volume method with Exact two-material Riemann problems) for CFD and FSI (2008-2015)
- 1D, exact, two-material, fluid-structure (half) Riemann problems for inviscid fluxes
- ghost-type fluid method for viscous fluxes
- nonlinearly stable (TVD)
- second-order accurate away from material interfaces
- first-order accurate at material interfaces
- insensitive to relative position/orientation
- smooth solution gradients at material interfaces
- handles topological changes (cracks, tears, ...)

EULERIAN FRAMEWORK

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EULERIAN FRAMEWORK
GOVERNING FLUID-STRUCTURE EQUATIONS

- Governing fluid equations

\[
\frac{\partial W}{\partial t} + F(W) = R(W, \nabla W) + \text{turbulence modeling}
\]

- Governing structure equations

\[
\rho_s \ddot{u}_s + \nabla \sigma_s (u_s, \dot{u}_s) = f_s \\
\sigma_s n^t = T \quad \text{on } \Gamma^t \\
u_s = u_s^D \quad \text{on } \Gamma^D
\]

- Fluid-structure interface

- slip (no-slip) \quad \nu n^{F/S} = \nu_s n^{F/S} \quad (\nu = \nu_s)

- equilibrium

\[
\left( \frac{1}{\det (\partial u_i / \partial x_j + \delta_{ij})} \right) \left( S_{km} + S_{kj} \frac{\partial u_m}{\partial x_j} \right) \left( \frac{\partial u_l}{\partial x_m} + \delta_{lm} \right) + p \delta_{kl} \right) n_k^{F/S} - T_l = 0
\]
TWO-MATERIAL PROBLEM

Finite volume semi-discretization of the Navier-Stokes equations

\[
\int_{\Omega} \frac{\partial W_h}{\partial t} \, d\Omega + \sum_{j} \int_{\partial C_{ij}} F(W_h) n_{ij} \, d\Sigma + \int_{\partial C_i \cap \Sigma_h} F(W_h) n_i \, d\Sigma + \int_{\partial C_i \cap \Sigma^f_h} F(W_h) n_i \, d\Sigma
\]

\[+ \sum_{\Omega^e \ni i} \int_{\Omega^e} R(W_h) \nabla N_i^e \, d\Omega = 0\]
Finite volume semi-discretization of the Navier-Stokes equations

\[ \int_{\partial C_{i,j}} F(W_h) n_{i,j} d\Sigma \approx \Phi(W_i, W_j, EOS_i) \quad (\text{i.e., Roe's flux function}) \]

\[ \int_{\partial C_{i,k}} F(W_h) n_{i,k} d\Sigma \approx \Phi(W_i, W_{ik}^*, EOS_i) \]

how to obtain \( W_{ik}^* \) at the material interface?
Formulate and solve an exact half Riemann problem
- at a \textit{surrogate material interface} $\Gamma^*$

\[ \frac{\partial w}{\partial t} + \frac{\partial F(w)}{\partial \xi} = 0 \]

\[ w(\xi, 0) = w_\perp \quad \text{if} \quad \xi \geq 0 \]
\[ v(v_s, t) = v_{s\perp} \quad \forall \quad 0 \leq t \leq \Delta t \]

$\Gamma^*$: surrogate material interface

$\Gamma$: true material interface
EFFECTS OF GEOMETRIC ERROR

- Formulate and solve an exact half Riemann problem
  - at a \textit{surrogate material interface} $\Gamma^*$

- 2\textsuperscript{nd}-order FV semi-discretization away from the interface
- semi-discretization (SD) error $O(h/2)$ of the geometric type
  - local SD error $O(1)$ (inconsistent method at $\Gamma^*$)
  - global SD error $O(h)$ ($1^{\text{st}}$-order method)
Formulate and solve an exact half Riemann problem - at the *true material interface* $\Gamma$

- $2^{nd}$-order FV semi-discretization away from the interface
- $2D/3D$: SD error $O(h^2)$ of the geometric type (shape)

- $2^{nd}$-order convergence

local SD error $O(h)$

global SD error $O(h^2)$ ($2^{nd}$-order convergence)
EXTENSION TO VISCOUS FLOWS

- P1 approximation of the diffusive fluxes
  - standard Galerkin Finite Element (FE) approximation

\[
\int_{\Omega^e} R(W_h) \nabla N_i^e \ d\Omega = |\Omega^e| \sum \beta_j \nabla N_i^e \ R(V^e(x_j), \nabla V^e(x_j))
\]

\[
V^e = \frac{1}{n^e} \sum_k V_k N_k^e, \quad \nabla V^e = \frac{1}{n^e} \sum_k V_k \nabla N_k^e
\]

- linear reconstruction of the velocity

\[
v_j = v_i + \frac{ij}{|ij|_{ij}} (v_s(l_{ij}) - v_i)
\]

- constant/linear reconstruction of the temperature
  (adiabatic/isothermal)

- linear reconstruction of the turbulent variables
Embedding a computational model
- beam elements or other FE representation of cable
- embedded discrete (true) surface $\Sigma$ of cable
  - matching of $\Sigma$ and cable model
  - master/slave kinematics

- load transfer from the embedded discrete surface to the CM

\[
\begin{align*}
x_S^0 &= x_M^0 + d \\
u_S &= u_M + Rd - d \\
\dot{u}_S &= \dot{u}_M + \omega \times Rd
\end{align*}
\]

\[
F_M = F_S \\
P_M = P_S + Rd \times F_M
\]
Compactness and randomness of initial folding pattern

Traditional folding patterns & Space-Filling Curves (SFC): \([0,1] \rightarrow [0,1]^d\)
Ergun equation

\[ \frac{dp}{dr} = a(\mu, \alpha)v_{\text{rel}} + b(\rho, \alpha)v_{\text{rel}}^2 \]

where \( a \) and \( b \) denote the viscous and inertial porosity coefficients and depend on the viscosity \( \mu \) and porosity \( \alpha \).

(velocity is assumed to be continuous and flow compressibility effects are neglected)

FIVER with homogenized porosity model
- velocity is not assumed to be continuous & flow is compressible
- material porosity is elegantly treated using FIVER and a homogenized porosity model based on \( \alpha = \) pore volume ratio
FIVER with homogenized porosity model

\[ \Phi_{ij} = \alpha \Phi_{Roe}(W_i, W_j) + (1 - \alpha) \Phi_{Roe}(W_i, W_i^R) \]

- convective fluxes

- averaged reconstructed ghost velocity for diffusive fluxes
  \[ v_{j,ave}^g = \alpha v_j + (1 - \alpha) v_j^g \]

- \( \alpha \) can be deterministic or stochastic
MODELING MATERIAL POROSITY

- Model validation using direct simulations (Mars atmosphere)
  - $M_\infty = 1.8$, $P_\infty = 260 \, Pa$, $\rho_\infty = 6.7 \times 10^{-3} \, kg/m^3$, $\alpha = 0.02$

pore-level numerical simulation

predicted aerodynamic drag
Canopy (F-111 nylon)
- $th = 7.607 \times 10^{-5} \, m$
- hyperelastic plane stress
- $E = 9.45 \times 10^8 \, Pa, \ \nu = 0.4, \ \rho = 1.15425 \times 10^3 \, kg/m^3$
- geometric nonlinearities
- porosity: 0%, 1%, 2% and 10%

Suspension lines
- $l = 2 \, m, \ r = 1.6 \times 10^{-3} \, m$
- $\rho = 1.15425 \times 10^3 \, kg/m^3$
- linear elastic
- $E = 1.29 \times 10^{10} \, Pa, \ \nu = 0.3$
- geometric nonlinearities

Supersonic flows
- $H = 10,000 \, m: \ M_\infty = 2.0, \ P_\infty = 10^4 Pa, \ \rho_\infty = 0.6 \, kg/m^3$
CAPTURING THE DYNAMICS OF SUSPENSION LINES
Hilbert (left) and “Sine” (right) folding patterns
EFFECTS OF THE FOLDING PATTERN

Drag time-histories (S folding pattern)

Ignoring the "flat" curve

- relative maximum difference at any time = 131%
EFFECTIONS OF THE FOLDING PATTERN

- Maximum von Misses stress time-histories

- Ignoring the “flat” curve
  - relative maximum difference at any time = 300%!
EFFECTS OF MATERIAL POROSITY

URANS-Based FSI Simulations — S folding pattern

2% material porosity

10% material porosity
3D PID SIMULATIONS — DGB SYSTEM

- FE structural model of canopy
  - 99,836 elements: beams and shells
  - 56,280 nodes and 337,680 dofs
  - $R = 7.7 \text{ m}, \ th = 7.61 \times 10^{-5} \text{ m}$
  - F111 nylon: hyperelastic plane stress
  - $E = 9.45 \times 10^8 \text{ Pa}, \ \nu = 0.4$
  - $\rho = 1154.25 \text{ kg/m}^3$
  - \textit{geometric nonlinearities}
  - explicit central difference

- FE structural model of suspension lines
  - $l = 36.56 \text{ m}, \ r = 1.6 \times 10^{-3} \text{ m}$
  - linear elastic: $E = 1.29 \times 10^{10} \text{ Pa}, \ \nu = 0.3$
    - $\rho = 1154.25 \text{ kg/m}^3$
  - \textit{geometric nonlinearities}
  - explicit central difference
Viscous CFD model
- embedding grid
  - 29.9 million tetrahedra, 4.9 million nodes
- embedded discrete surface
  - 69,756 triangles and 35,638 nodes
  - porosity: 2%
- URANS with Spalart-Allmaras turbulence mode
- fast distance to the wall computational algorithm (next talk)
- second-order, explicit Runge-Kutta (RK2)
- no AMR

Supersonic flow
- $H = 5$ to $11\ km, M_\infty = 1.8, P_\infty = 260\ Pa, \rho_\infty = 6.7 \times 10^{-3} kg/m^3$
Pressure field
Displacement magnitude
CONCLUSIONS

- Eulerian computational framework for parachute inflation dynamics
  - robust
    o large motions/deformations and massive self-contact
    o shocks and turbulence (URANS, LES in the near future)
  - comprehensive
    o geometric porosity
    o material porosity (with flow compressibility effects)
    o fluid-structure coupling for the suspension lines
    o folding patterns
    o handles topological changes (tears, cracks)

- Preliminary results
  - moderate to strong effects on performance of
    o material porosity
    o fluid-structure coupling at the suspension lines
    o folding pattern