Forge: A Cartesian Immersed-Boundary Approach to Unsteady Transonic Flow

Without Turbulence Modeling, Wall Functions, or Artificial Dissipation

Solver	Description
Algorithm	Semi-Lagrangian advection + spectral pressure projection
Turbulence	None (implicit LES)
Wall treatment	Physics-based molecular interface model
Precision	float64 throughout, PyTorch GPU
Hardware	NVIDIA RTX A4000 (16 GB), single GPU
Implementation	~3,200 lines Python (one file)

Precision & Data Integrity

`float64`

Every field. Every operation. Every step.

Bit-perfect checkpoint resume

Run → stop → restart → identical results

Verified on ONERA OAT15A

Full 3D fields saved to HDF5

`u, v, w, p, T, ρ, div(u) per step`

LZF compressed. Any quantity extractable post-hoc.

Ben Eugster | Forge Physics LLC | DPW-8 / AePW-4 | June 2026

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Method: Frozen-State Architecture

Globally-synchronized explicit timestep

1. Freeze entire field state at time t
2. Compute ALL domain tendencies simultaneously from that snapshot
   (fluid, thermal, structural, electromagnetic — all see same state)
3. Sum tendencies and project forward once

No iterative coupling between domains
No matrix inversions or inner iterations
No sequential update contamination

Unconditionally stable: CFL > 10^{31} recorded without divergence

Solver Components

Component	Approach
Advection	Semi-Lagrangian (3D trilinear backtrack)
Pressure	Spectral (FFT) Leray projection
Wall BC	Molecular accommodation interface
Turbulence	None — implicit LES from scheme
Dissipation	Zero artificial dissipation
Density	Active transport + equation of state
Diagnostics	Proprietary info-theoretic scalar

Method: Wall Interface — No Turbulence Model

How does it work without a turbulence model?

The wall is not a mathematical boundary condition.
It is a physics-based interface between two materials.

Momentum exchange is governed by the molecular accommodation coefficient between the fluid and wall material. The velocity field near the wall develops naturally through that exchange — outward through advection and diffusion. No prescribed velocity profile.

Grid considerations:
Uniform Cartesian. No stretching, no clustering, no aspect ratio management. The consideration is cells per chord and domain extent. Surface interaction is in the interface physics, not in the mesh.

Conventional vs. Forge

	Conventional	Forge
Wall BC	Wall function or $y+ < 1$	Molecular interface
BL mesh	52+ layers s=1.2 growth	Uniform Cartesian
Turb model	SA, SST k-ω, DDES, etc.	None
Dissipation	Flux limiters, artificial visc.	Zero
Grid effort	Weeks	Minutes

Geometry Pipeline: CAD to Simulation

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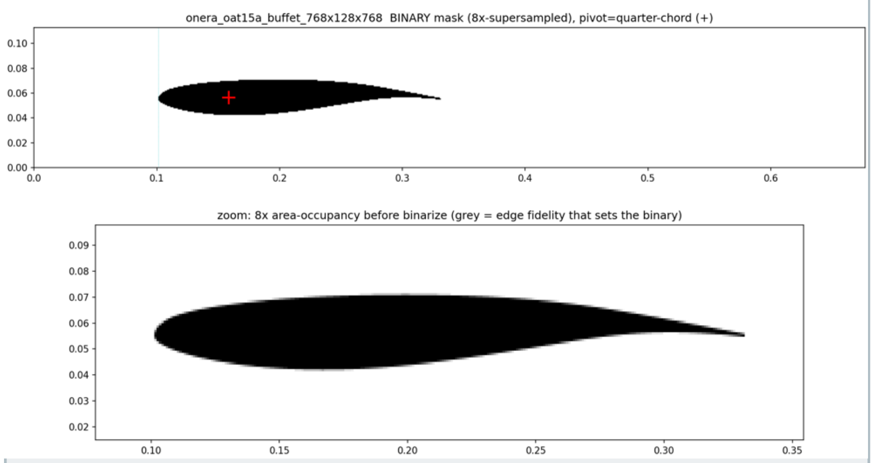
IGES/STEP CAD ▶ Part Extraction ▶ Watertight Wrap ▶ 4× Super-sample ▶ Block Average ▶ NPY Mask + Config

ONERA OAT15A Grid Specification

Parameter	Value
Grid	768 × 512 × 16
Total cells	6,291,456
dx, dy, dz	1.198, 1.797, 1.438 mm
Domain	0.92 × 0.92 × 0.023 m
Chord (c_ref)	230 mm (model scale)
Cells/chord	~192 (streamwise)
Surface samples	17,136
Span cells	16 (10% chord)



ONERA OAT15A: Test Case Setup

Condition	Value	Source
Mach	0.7303	DPW-8 TC1
Angle of attack	3.78°	Geometry rotated in conversion°
U_∞	241.0 m/s	From Mach + T_static
ρ_∞	0.923 kg/m³	Experimental condition
T_static	271.0 K	Experimental condition
q_∞	26,804 Pa	$\frac{1}{2}\rho U^2$
c_sound	330.0 m/s	$\sqrt{(\gamma RT)}$
dt	1.0×10^{-4} s	Explicit timestep
Steps analyzed	750 (steps 751–1500)	Post-transient window
Boundary	Tunnel mode, open walls	Inlet/outlet + open lateral

Note: OAT15A geometry per ONERA designation. Model-scale chord = 230 mm.

ONERA OAT15A: Convergence & Force History

Quantity	Mean	Range (unsteady)	Δ (counts)
CD	0.0389	0.0333 – 0.0427	94
CL	0.1908	0.1822 – 0.1973	151
CM	0.3064	0.2906 – 0.3187	281

1 drag count = 0.0001. CD swing of 94 counts indicates significant unsteady force oscillation.

Diagnostic convergence (D):

Step	D	Status
0	0.9997	Initial (uniform field)
1	0.0632	95% resolved
5	0.0075	99.3% resolved
1500	0.0227	Settled unsteady limit-cycle

Spectral characteristics:

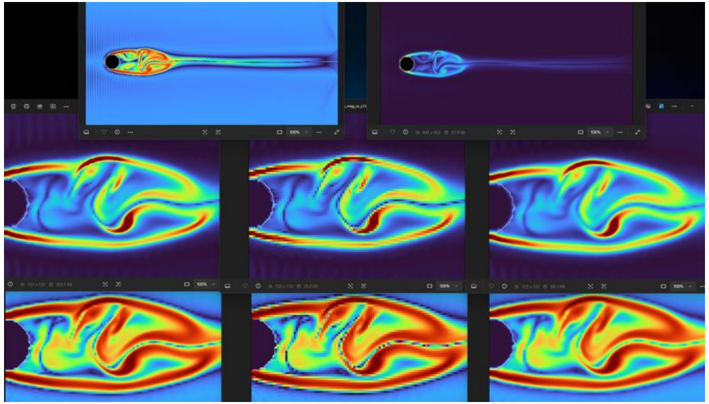
Probe location: x/c = 0.45
(upper surface, mid-chord)

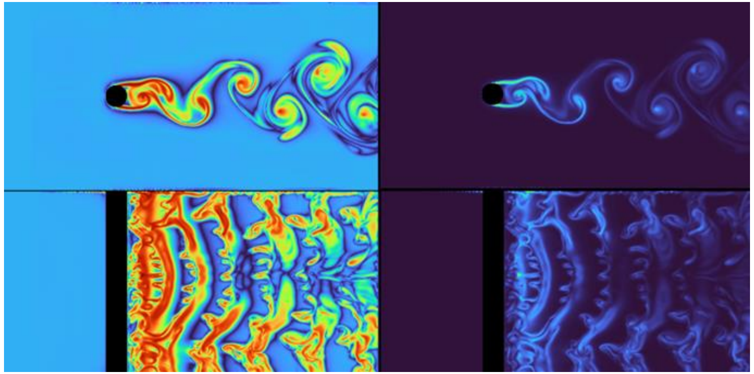
Analysis window: 750 steps
dt = 1.0×10^{-4} s
Nyquist: 5,000 Hz

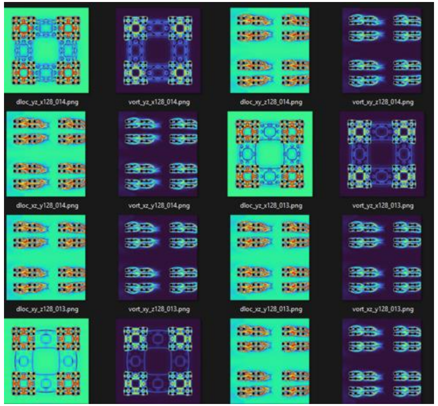
Peak PSD at 13.3 Hz
(0.0112 Pa^2/Hz)

Broadband content above 100 Hz consistent with turbulent buffet

Reference: Jacquin et al. 2009



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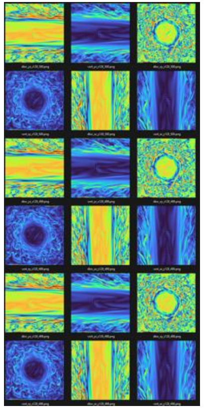

Summary & Next Steps

What we showed:

A Cartesian immersed-boundary solver that resolves unsteady transonic flow — including shock buffet — without turbulence modeling, wall functions,
or artificial dissipation. Running on consumer workstation hardware.

Next steps:

Grid refinement studies on ONERA OAT15A
Full AoA sweep for buffet onset characterization
NASA CRM force/moment polar completion
Aeroacoustic analysis from div(u) field data

Post-workshop:

Interested in aligning with the Source of Scatter Working Group
and the Buffet Working Group for continued collaboration.

Thank you

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Questions welcome.