Formulation and Implementation of Inflow/Outflow Boundary Conditions to Simulate Propulsive Effects

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Cart3D Aerodynamic Analysis & Design Package

- Automated multilevel Cartesian mesh generation with adjoint-driven adaptive refinement
- Cut-cell approach in cells that include model surface
- Finite volume, 2nd-order accurate Euler solver with explicit Runge-Kutta time stepping and multigrid
- Steady or time-accurate
- Part of a design framework allowing for gradient-based aerodynamic shape optimization of user-specified functional
- Shown to be highly effective for analysis and design of low boom aircraft
Motivation for New Boundary Conditions

• Current **SurfBC** inflow/outflow boundary condition requires user to specify an entire state \((\rho, u, v, w, p)\) at the boundary (Pandya, 2004)
  
  • Riemann solver is applied to compute flux at the boundary and thus boundary condition is always well-posed
  
  • Robust and flexible since it can be used for both inflow and outflow, subsonic and supersonic
  
• Inconvenient when user wants to specify inflow or outflow with minimal information
  
  • for subsonic flow through inlets, a common boundary condition is back pressure
  
  • for subsonic flow into nozzles, a common boundary condition is specifying total pressure and total temperature (and flow direction)
  
  • very difficult to specify mass flow rate, particularly in cases where nonlinear flow features are prevalent
Cart3D Surface Boundary Conditions

• Solid wall

• Specify full flow state and use Riemann solver (*SurfBC*)
  - Pandya, Murman, Aftosmis, 2004
  - for all inflows and outflows

• Subsonic Outflow
  - back pressure
  - constant normal velocity

• Subsonic Inflow
  - total pressure and total temperature
  - mass flow rate and total temperature
Subsonic Outflow Boundary Conditions

• One flow quantity specified at boundary
  • back pressure
  • normal velocity

• Four flow quantities extrapolated from interior
Back Pressure Outflow

- Most other CFD solvers have this common option
- Pressure set to specified value at boundary
- Entropy and tangential velocity extrapolated from interior
- Riemann invariants used to compute boundary state
- Safeguards
  - if flow reverses back into interior (back pressure too high), solid wall boundary enforced
  - if interior flow goes supersonic, compare back pressure to pressure after normal shock occurring at boundary
    - if set back pressure is higher, use after-shock state at boundary, forcing subsonic flow in the interior
    - if set back pressure is lower, extrapolate all flow attributes from interior (supersonic outflow)
- Can be difficult to obtain specific mass flow rate for nonlinear flows
Constant Normal Velocity Outflow

- Allows for robust mass flow rate steering
- Might better represent flow in front of an engine fan face (Pearson ’59, Reid ’69)
- Normal velocity set to specified value at boundary
- Entropy and tangential velocity extrapolated from interior
- Riemann invariants used to compute boundary state
- Safeguards
  - when interior flow is subsonic but boundary flow is supersonic (bad input velocity), flow is forced to be sonic (choked flow)
  - when interior and boundary flow are both supersonic, supersonic outflow is enforced (all interior quantities extrapolated)
Subsonic Inflow Boundary Conditions

- Four flow quantities specified at boundary
  - velocity set to be normal to boundary (two flow quantities)
  - total pressure and total temperature
  - mass flow rate and total temperature
- One flow quantity extrapolated from interior
Stagnation Property Inflow

- Most other CFD solvers have this common option
- Total pressure and temperature set to specified value at boundary
- Tangential velocity set to zero, forcing inflow to be normal to surface
- Enthalpy is extrapolated from interior
- Riemann invariant used to computed boundary state

**Safeguards**
- when flow tries to reverse back into boundary, solid wall boundary enforced
- inflow Mach number is limited to sonic, adjusting stagnation properties accordingly
- Cannot explicitly set a mass flow rate

\[
\begin{align*}
\hat{n} \\
p_{t,\text{set}} \\
T_{t,\text{set}} \\
V_{t,\text{b}} &= 0 \\
V_{n} \\
H_{t,i}
\end{align*}
\]
Mass Flow Rate and Total Temperature Inflow

- Allows for explicit mass flow rate control
- Mass flow rate and total temperature set to specified value at boundary
- Tangential velocity set to zero, forcing inflow to be normal to surface
- Density is extrapolated from interior
- Boundary flux computed from boundary state

Safeguard
- Inflow Mach number is limited to sonic, adjusting boundary values accordingly
Mass Flow Rate Control

• Constant velocity outflow boundary condition can be steered to obtain specified mass flow rate out of the domain
  • average density over surface is computed
  • velocity out of domain is set based on desired mass flow rate
  • repeat every few iterations until solution converged and mass flow rate within tolerance
Mass Flow Rate Control

• Constant velocity outflow boundary condition can be steered to obtain specified mass flow rate out of the domain
  • average density over surface is computed
  • velocity out of domain is set based on desired mass flow rate
  • repeat every few iterations until solution converged and mass flow rate within tolerance

• Constant mass flow rate inflow boundary condition explicitly sets mass flow rate into the domain
Adjoint-Driven Adaptive Mesh Refinement

- All boundary conditions now implemented in adaptive mesh refinement process
- Updates to `adjointCart`, `xSensit`, `adjointErrorEstQuad`, etc.
Application of New Boundary Conditions

- Ducted fan in near-hover (subsonic)
  - verification of back pressure outflow and mass flow rate inflow boundary conditions
  - mesh convergence through adaptive refinement
  - mass flow rate steering example
- Turbofan with both fan and turbine exhaust streams (transonic)
  - verification of constant velocity outflow and stagnation property inflow boundary conditions
  - mesh convergence through adaptive refinement
  - mass flow rate steering example
- Turbojet with 2-D ramp inlet (supersonic)
  - mesh convergence through adaptive refinement
  - mass flow rate steering example
- Scramjet (hypersonic)
- Low boom demonstrator
- Validation cases
Ducted Fan in Hover

• Duct and center body housing motor to drive fan

• Very low freestream Mach number (0.001) to simulate near hover

• No angle of attack - axisymmetric flow

• Fan modeled as *annular disk*

• Inflow / Outflow boundary conditions enforced on disk to model fan effects
Ducted Fan - Example Solution

Back Pressure Outflow

Stagnation Property Inflow

M∞ = 0.001, α = 0°, 130M cells
Ducted Fan - Example Solution

Back Pressure Outflow

Stagnation Property Inflow

$M_{\infty} = 0.001$, $\alpha = 0^\circ$, 130M cells
Back Pressure B.C. Mesh Convergence

Contour of Pressure Error

$L_2$ norm of Pressure Error vs. Number of Cells
Ducted Fan - Example Solution

Constant Velocity Outflow

Constant Mass Flow Rate Inflow

$M_\infty = 0.001, \alpha = 0^\circ, 160M$ cells
Ducted Fan - Example Solution

Constant Mass Flow Rate Inflow

M̅ = 0.001, α = 0°, 160M cells

Constant Velocity Outflow
Constant Mass Flow Rate B.C. Mesh Convergence
Ducted Fan - Mesh Convergence

• Good convergence of functional (drag)
• Steady reduction in error estimate
Ducted Fan - Adaptively Refined Mesh

- Colors represent cells of same level of refinement
- Mesh was refined at surface, at shear layer of exhaust flow, and near attachment point

Attachment Point

Slipstream
Ducted Fan - Mass Flow Rate Steering

• Inflow mass flow rate ($m_{\text{inflow}}$) set through boundary condition

• Outflow mass flow rate ($m_{\text{outflow}}$) steered to match

• Mass flow rate quickly converges and continues to converge through each refined mesh
Ducted Fan - Example Solution

**Matched Mass Flow Rates**

$M_{\infty} = 0.001$, $\alpha = 0^\circ$, 180M cells
Turbofan in Transonic Flow

- Transonic diffuser with fan hub
- Two stream exhaust with cone nozzle for turbine flow
- Mach 0.8 freestream, no angle of attack (axisymmetric flow)
- Fan / Compressor face modeled as annulus, outflow boundary condition applied
- Fan and turbine exhaust planes modeled as annuli, inflow boundary conditions applied
Turbofan - Example Solution

Back Pressure Outflow

$M_\infty = 0.8, \alpha = 0^\circ, 170M$ cells

Stagnation Property Inflow

Mach Number: 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
Turbofan - Example Solution

$M_\infty = 0.8, \alpha = 0^\circ, 170M$ cells

Mach Number: 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
Stagnation Property B.C. Mesh Convergence
Turbofan - Example Solution

- Constant Velocity Outflow
- Constant Mass Flow Rate Inflow

$M_\infty = 0.8$, $\alpha = 0^\circ$, 160M cells

Mach Number: 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
Turbofan - Example Solution

Constant Velocity Outflow

$M_\infty = 0.8$, $\alpha = 0^\circ$, 160M cells

Constant Mass Flow Rate Inflow

Mach Number: 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
Constant Velocity B.C. Mesh Convergence
Turbofan - Mesh Convergence

- Good convergence of functional (drag)
- Steady reduction in error estimate
Turbofan - Adaptively Refined Mesh

- Colors represent cells of same level of refinement
- Mesh was refined at surface, at shear layer of inlet and exhaust flow, near attachment point, and at shock structures
Turbofan - Mass Flow Rate Steering

- Inflow mass flow rate ($\dot{m}_{\text{inflow}}$) set through boundary condition
- Outflow mass flow rate ($\dot{m}_{\text{outflow}}$) steered to match
- Mass flow rate quickly converges and continues to converge through each refined mesh
**Turbofan - Example Solution**

**Matched Mass Flow Rates**

\[ M_\infty = 0.8, \, \alpha = 0^\circ, \, 160M \text{ cells} \]
Turbojet in Supersonic Flow

- 2-D ramp inlet design for normal terminal shock
- Converging-diverging duct with cone nozzle
- Mach 1.5 freestream, 1° angle of attack
- Outflow / Inflow boundary conditions applied to annuli
Turbojet - Mesh Convergence

- Good convergence of functional (thrust + lift + plume sensor)
- Steady reduction in error estimate
Turbojet - Adaptively Refined Mesh

- Colors represent cells of same level of refinement
- Mesh was refined at surface, within Mach cone of influence, at shock and expansion structures, and at plume shear layer influencing pressure sensor
Supersonic Inlet - Mass Flow Rate

- Usually need to specify mass flow rate through an inlet
- Often desirable to match nozzle mass flow rate if modeled
- Highly nonlinear flow features can make mass flow rate steering difficult in supersonic and even transonic inlets
Turbojet - Mass Flow Rate Steering

- Inflow mass flow rate ($\dot{m}_{\text{inflow}}$) set through boundary condition
- Outflow mass flow rate ($\dot{m}_{\text{outflow}}$) steered to match
- Mass flow rate quickly converges and continues to converge through each refined mesh
Turbojet - Matched Mass Flow Rates

$M_\infty = 1.5$, $\alpha = 1^\circ$, 120M cells
Scramjet in Hypersonic Flow

- Multiple ramp inlet and outlet, flow through burner remains supersonic
- Mach 5.0 freestream, 2° angle of attack
- Subsonic inflow / outflow boundary conditions not applicable
- Original full state with Riemann solver (SurfBC) boundary condition applied
- Mesh was refined at surface, within Mach cone of influence, shock and expansion structures, and plume shear layer influencing pressure sensor
Low Boom Supersonic Demonstrator

- Realistically complex geometry
- Mach 1.4 freestream, 2.15° angle of attack
- 3 inlets and 3 exhausts
Low Boom Aircraft - Adaptively Refined Mesh

- Functional was aircraft drag
- Colors represent cells of same level of refinement
- Mesh was refined at surface, within Mach cone of influence, and at shock and expansion structures
Low Boom Aircraft - Example Solution

- Underwing inlet geometry is not fully realized
- Safeguards were active in these inlets (solid wall to not allow reverse flow)

\( M_\infty = 1.4, \alpha = 2.15^\circ, \)  
70M cells (half-body mesh)
Validation Case - 2-Shock Inlet

• Same validation case was run with SurfBC (Pandya, 2004)
Verification Case - Low Boom Demonstrator Signature

- Low boom aircraft was analyzed original SurfBC and again new boundary conditions
- Near field signatures compared

![Graph showing distance along sensor vs. ∆p/p for h/L=3, 0deg. The graph compares New BCs (red) and Old BCs (blue).](image)
Summary and Ongoing Work

• Four new subsonic inflow/outflow boundary conditions implemented to improve modeling of propulsion systems

• Robust mass flow rate control implemented for both inflow and outflow

• Demonstrated on notional propulsion systems in flight regimes ranging from subsonic to hypersonic
  • adjoint-driven mesh refinement demonstrated with all propulsion boundary conditions
  • new boundary conditions verified mesh convergence studies on notional examples

• Demonstrated on realistically complex low boom aircraft

• Some validation completed

• Ongoing work
  • Implement additional functionals appropriate for propulsion systems
  • Extend design framework to include new propulsion boundary conditions and functionals
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