Conceptual Design for a Dual-Bell Rocket Nozzle System Using a NASA F-15 Airplane as the Flight Testbed

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Introduction

Dual-Bell Rocket Nozzle Technology

- The dual-bell rocket nozzle has predicted benefits
  - Potential to increase nozzle performance over the integrated rocket trajectory
  - Potential to reduce engine side loads during low-altitude operation
- Predicted benefits could have a significant impact
  - Nozzle performance could increase the mass payload capability to LEO
- TRL advancements have been slow, despite the predicted benefits
  - 1949: Concept first appeared in literature
  - 1993: First publication on static testing
  - 2014: Still requires adequate testing in a relevant flight environment
- Predicted benefits warrant investigation in a relevant flight environment

Dual-bell nozzle testing at NASA Marshall
Introduction
Taking the Dual-Bell Rocket Nozzle to Flight

- Proposal was constructed to advance dual-bell nozzle through flight
  - Plan to utilize a NASA F-15 airplane as the flight testbed, with the Propulsion Flight Test Fixture (PFTF) and Rocket Forebody Simulator (RFS)
  - Captive-carried flight permits several benefits over free-flight with a rocket
  - Traceability to NASA goals, as well as Armstrong and Marshall expertise

- Flight research campaign includes three phases:
  - Phase I: External flow-field flights
  - Phase II: Cold-flow nozzle operation
  - Phase III: Reacting-flow nozzle operation

- Current effort details feasibility on Phase I and Phase II flight activity
  - The conceptual design for Phase III will be detailed in a future publication
Conceptual Design for Phase I Flights
External Flow-Field Conceptual Design

- Extensive utilization of existing flight-proven hardware
- Phase I primary objective: Quantify the F-15 external flow field
  - RFS outer mold line (OML) will be heavily instrumented
  - Flight data to validate CFD flow-field predictions
- External flow-field data will be obtained at all conditions where nozzle operation will occur (during Phase II and Phase III)
Initial external flow-field analysis conducted to assess feasibility
- Utilized the Star-CCM+ polyhedral finite-volume unstructured CFD code
- CFD flow-field analysis with inviscid/Euler assumptions
- Analysis included two test points (Mach 0.9 and Mach 1.2), both at 46 kft
- Considered worst-case flow-field scenario, with blocked F-15 engine inlets

Initial evaluation of model compared against a clean F-15 airplane
- Results reveal no local flow anomalies when including PFTF and RFS
Analysis included evaluation of flow field during nozzle operation
- Realistic assessment of nozzle exit pressures (which are sub-ambient)

Initial results indicate a well-chosen location for nozzle experiment
- Analysis reveals no areas of concern in the local flow field
- Initial analysis adds greater confidence to operational feasibility

F-15 airplane with PFTF and RFS, Mach 1.2, with nozzle operating

Dual-bell nozzle during operation on F-15 airplane at Mach 1.2 (RFS made invisible to show nozzle)
Conceptual Design for Phase II Flights
Propellant Feed System Design (1 of 2)

- Phase II flights will include cold-flow \((\text{GN}_2)\) nozzle operation
  - Allows cold-flow static test data to be leveraged
  - Permits an intermediate/build-up approach in system complexity
- Entire propellant feed system is contained within the PFTF and RFS
  - PFTF will include tanks and controls, and routed to nozzle in the RFS
  - Pressure Reducing Assembly (PRA) plate for mounting controls
- Phase II conceptual design adds confidence to packaging feasibility
• System is designed for mission success and flight safety
  ▪ Permits monitoring and control by flight test engineer in back seat of F-15
  ▪ Enables a real-time and post-flight assessment of health and performance

Propellant feed system schematic and instrumentation
Conceptual Design for Phase II Flights
Dual-Bell Nozzle Design Philosophy (1 of 2)

- Design philosophy: Maximize dual-bell nozzle performance
  - Long-term goal: Integrate a dual-bell nozzle into a production rocket engine
  - Conceptual design objective: Demonstrate dual-bell nozzle flow control

- The Space Shuttle Main Engine (SSME) provides an excellent example for illustrating dual-bell nozzle performance benefits
  - NPR = Nozzle Pressure Ratio
  - NNPR = Normalized Nozzle Pressure Ratio

\[
NNPR = \frac{NPR}{NPR_{design}} = \left( \frac{P_c}{P_{amb}} \right) \left( \frac{P_c}{P_{amb}} \right)_{design}
\]

- Off-design NPR is apparent
- Standard throttling capability lends itself to dual-bell nozzle performance optimization

Typical engine parameters on the STS/SSME
• Any conventional-bell nozzle has significant performance losses
• Any nozzle design requires several trades to be made
  ▪ Optimized performance at launch competes with optimized vacuum $I_{sp}$
• Theoretically, a dual-bell nozzle can mitigate performance losses
One-dimensional nozzle sizing trades were completed with GN$_2$
- Varied nozzle throat diameter
- Varied ambient pressure

- Evaluated several performance parameters
  - Mass flowrate
  - Mass fraction consumed per test
  - Thrust (for mode 1 or mode 2 operation)

- Design space available to develop a test article of reasonable size
- Sizing trades add confidence to feasibility of nozzle operation in flight on the F-15 airplane

Thrust generated as a function of throat size, back pressure, and operational mode.
Conclusion

- The dual-bell nozzle should be tested in a relevant environment
- A conceptual design for Phase I flight was completed
  - Builds on existing flight-proven hardware
  - External flow-field predictions reveal no local flow areas of concern
- A conceptual design for Phase II flight was completed
  - Propellant feed system design fits within F-15 PFTF and RFS constraints
  - Design based on utilization of existing engine throttling capabilities
  - Dual-bell nozzle design approach will demonstrate nozzle flow control
  - Nozzle sizing trades reveal reasonable design space
- Design and operation of a dual-bell nozzle system with the NASA F-15 airplane as a flight testbed appears to be technically feasible
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