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Multiobjective Aerodynamic Optimization of a Supersonic Turbine for Higher Efficiency and Smaller Load Fluctuation

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Abstract

In a large thrust cryogenic fuel rocket engine, turbopumps are often the most stressed component in the system. Two important criteria in the design of turbopump systems are efficiency and reliability. Though one can easily formulate an optimization problem for higher efficiency, formulation for higher reliability is far trickier. The present study addresses this issue by optimizing for higher aerodynamic efficiency and smaller aerodynamic load fluctuation simultaneously as a multi-objective design exploration. The turbine stage is based on the NASA M-1 rocket turbine[1], scaled to match the operating requirement for an LE-5-class rocket engine[2] utilizing an expander-bleed cycle. The turbine is of supersonic impulse design, thus significant losses exist due to unsteady shock waves. The shock-shock and shock-boundary-layer interactions also contribute to a violent fluctuation of aerodynamic load experienced by the rotor disk. The load fluctuation was evaluated for each design candidate by running multiple frozen-rotor simulations at three nozzle-rotor phase angles.

In order to reduce the simulation turn-around time, flow analysis was carried out in quasi-3D RANS model, in which the spanwise variation in flow field was neglected. An in-house optimization environment was used for the optimization. Its algorithm is based on the Strength Pareto Evolutionary Algorithm 2[3] assisted by the use of Radial Basis Function Network as surrogate models[4, 5] which are enriched on-line at every outer iteration without the intervention of the user.

The validity of this approach, chosen for its computational efficiency, was examined *a posteriori* by comparing it against unsteady RANS simulations of the non-dominated designs. It was found that the optimal designs remained superior to the reference design even after the objective functions were re-evaluated from the URANS results, although the improvements, both in terms of efficiency and load fluctuation, were not as large as the RANS-based results. A closer look at the Pareto front, however, revealed that the relative positions of some of the non-dominated designs in the objective function space were different in the URANS results. Finally, the first-order effects of the design parameters on the objective functions were analyzed from the database of evaluated designs using Sobol indices. It was found that the leading edge metal angle and the curvature of the aft suction side are the most influential, with the former affecting the detached bow shock and its impingement on the neighboring rotor blade, and the latter affecting the strength of the shock in the rotor passage exit which also influences the wake thickness.

References

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