Power Optimal Control Allocation for Distributed Electric Propulsion in a Series/Parallel Hybrid Powertrain

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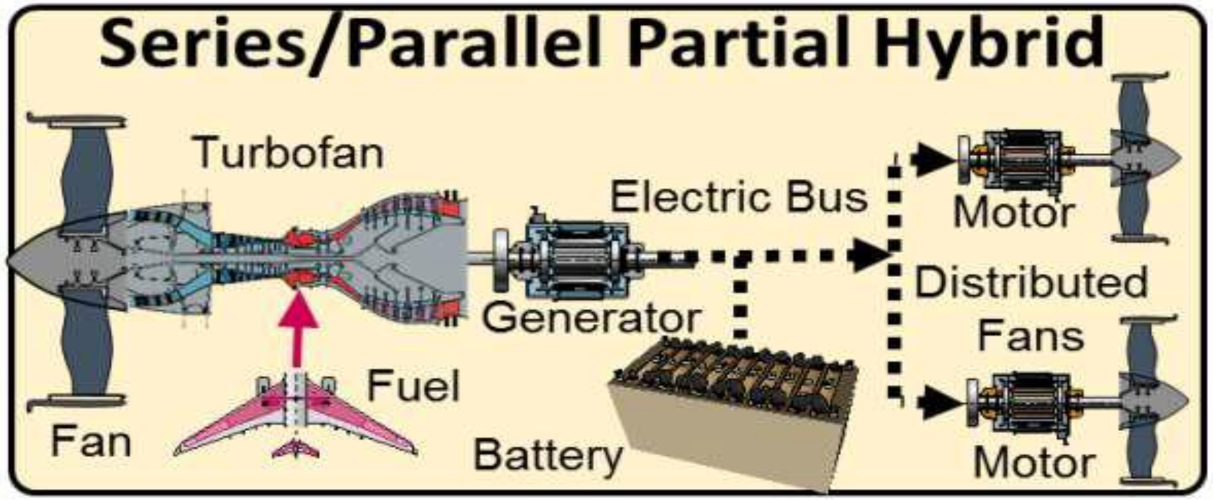
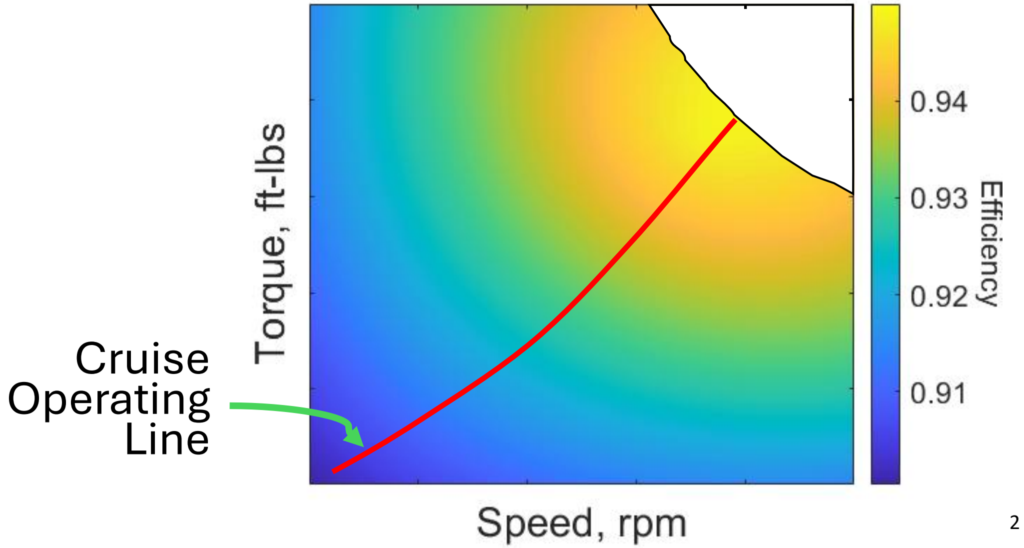
Electrified Aircraft Powertrains Contain Multiple Components From Power Source to Load

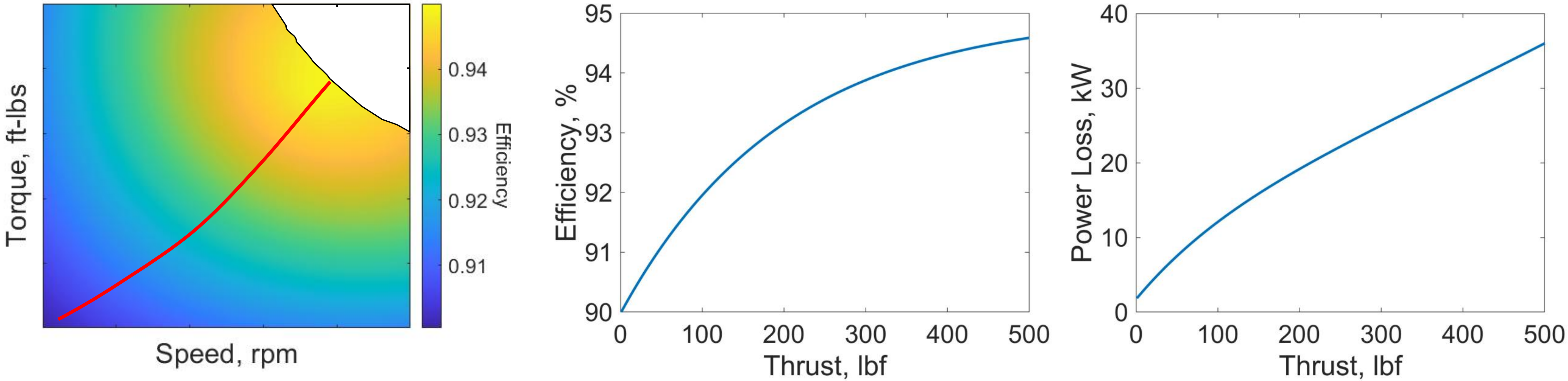
- Each component has operating regions where it is most efficient
- Electrical components should be optimized for overall system-level benefits
- The powertrain should be designed to be most efficient at the operating point at which it spends the most time, e.g., cruise
- However, there are potentially additional optimizations to be made regarding how the system is used that improve efficiency further





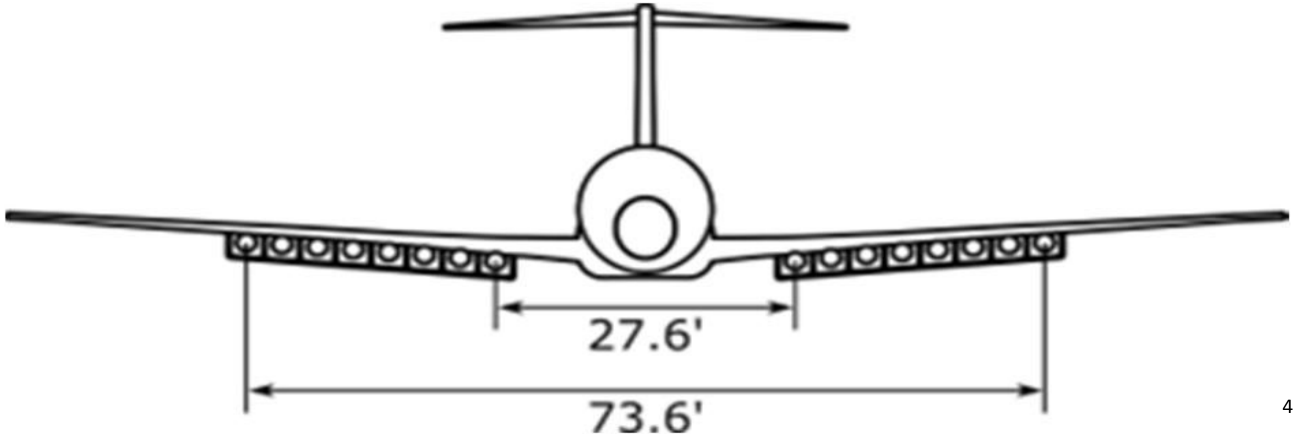
Efficiency of Operation and Power Loss

- Generally, efficiency is lowest at low speed/low torque condition
- Generally, efficiency is highest at high speed/high torque condition
- Although lower efficiency, little power lost in low power operation
- Here, efficiency slope is always positive but decreases with thrust
- There is a linear relationship between thrust and power



Examples

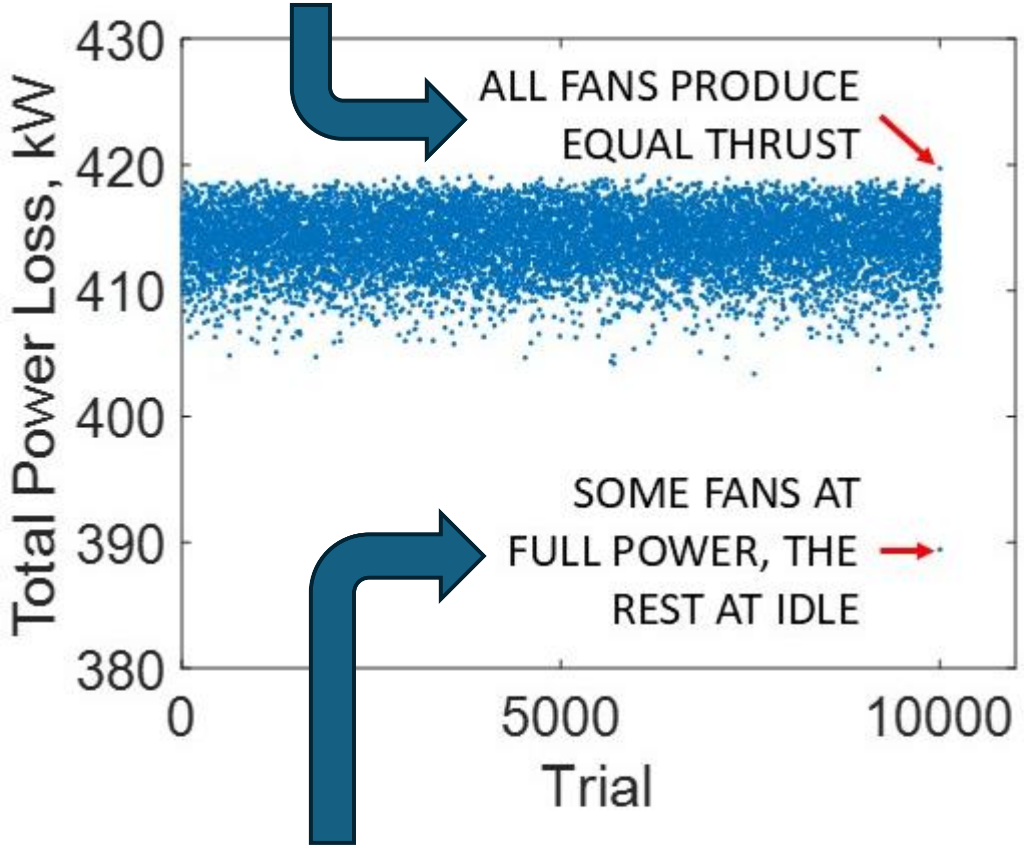
- Distributed electric propulsion aircraft
- 16 underwing fans, eight per side
- Cruise thrust range 26-500 lbf per fan
- Objectives are to:
  - maintain desired total net thrust
  - maintain net torque in the yaw axis due to thrust on the aircraft
  - minimize power loss



Example 1: Single Cruise Point

- Total thrust of 5156 lbf demanded
- Zero net torque about the yaw axis
- 10,000 cases were simulated
- Thrust values between 26-500 lbf were assigned randomly with a uniform distribution to 14 of the 16 fans, selected at random
- Thrust setpoints of the remaining two were set to meet the total thrust and net yaw axis torque requirements, if possible
- Otherwise, a new set of thrusts was assigned until a feasible set was achieved
- The optimal solution has 10 fans at full power and six at idle

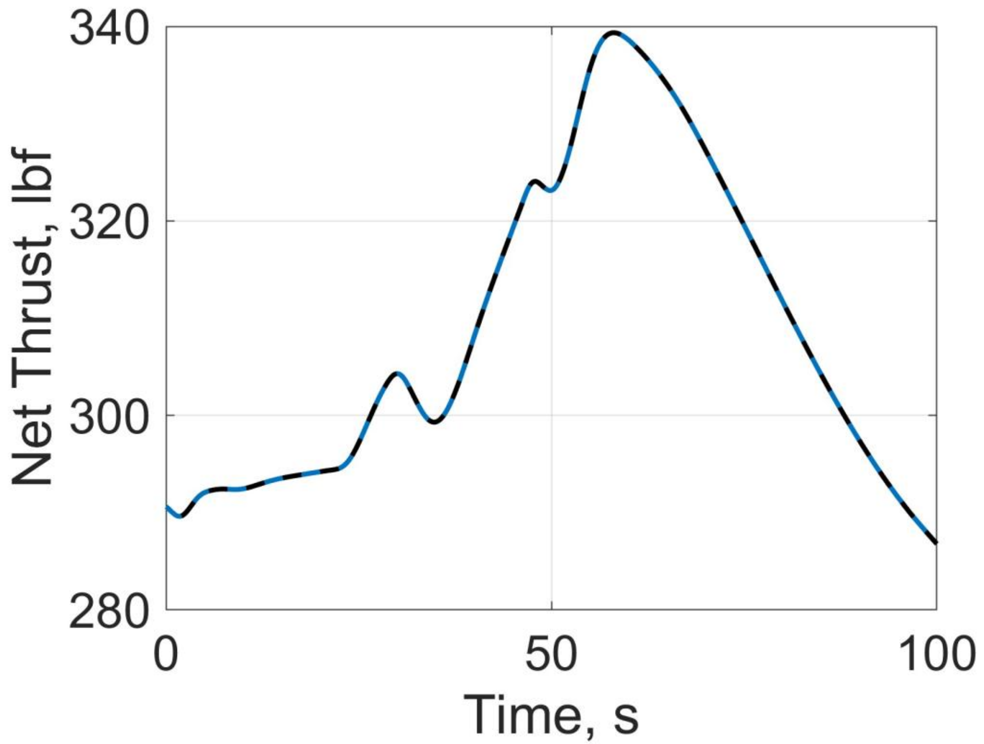
All at the same power (5156 lbf/16) maximized power loss

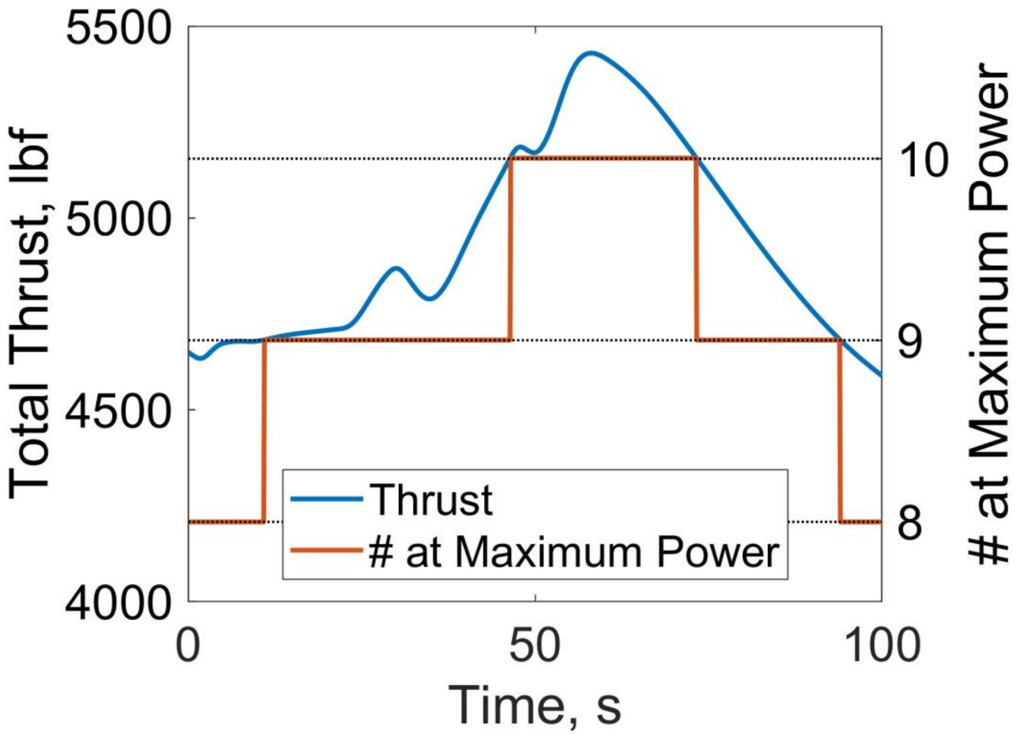


10 at maximum power, six at low power minimized power loss

Example 2: Cruise Thrust Level Change

- Baseline: All 16 individual fans move together
- Most possible at maximum power varies throughout transient





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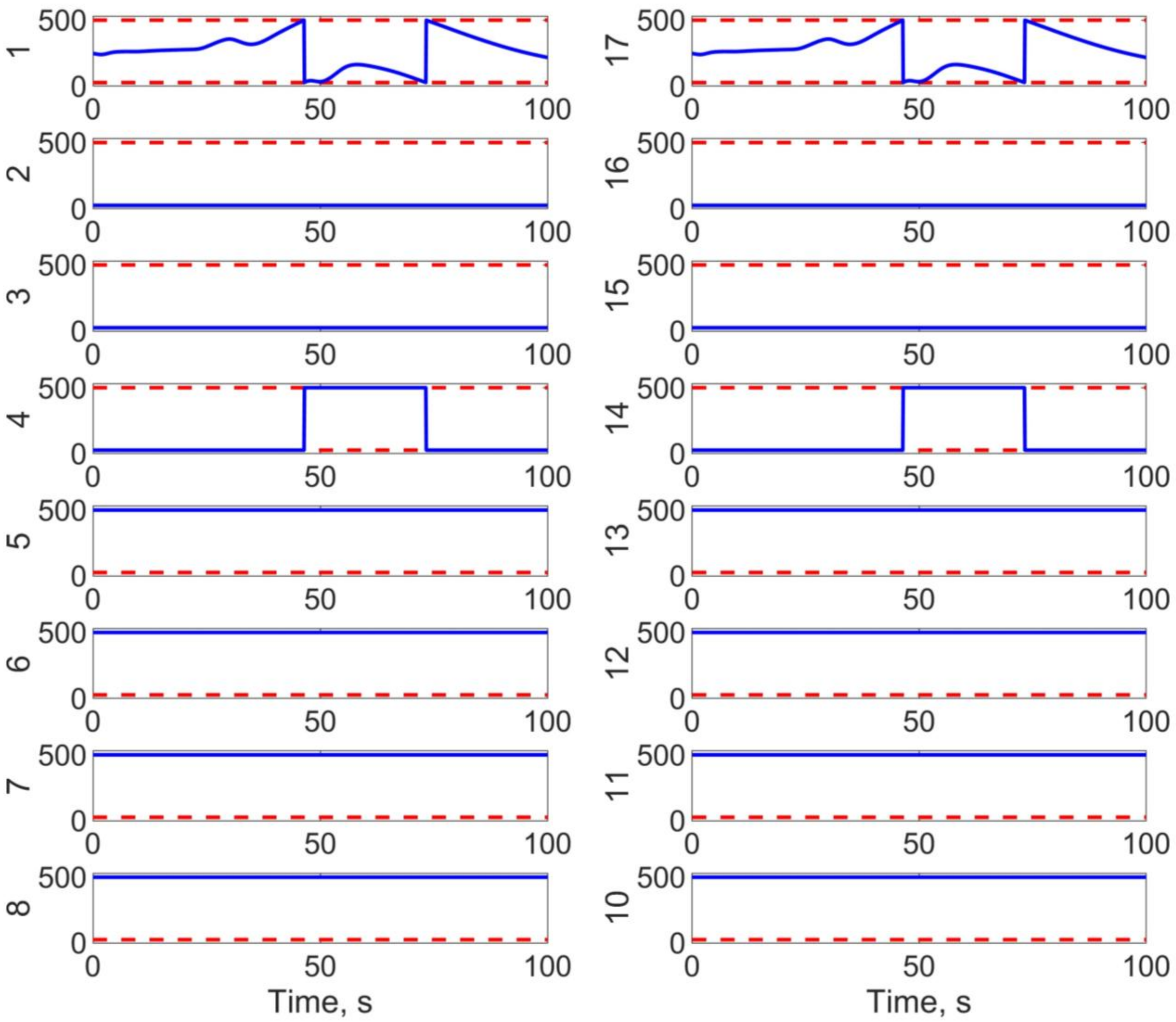

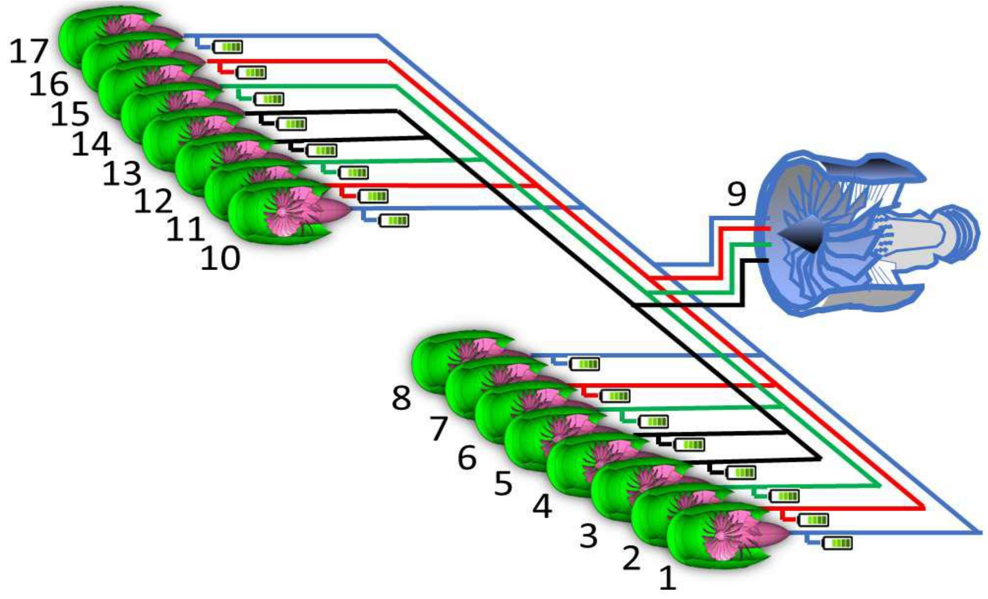

- Fan commands are symmetric
- Innermost are at high power
- Further back are at low power
- Outermost adjust to meet thrust and torque requirements

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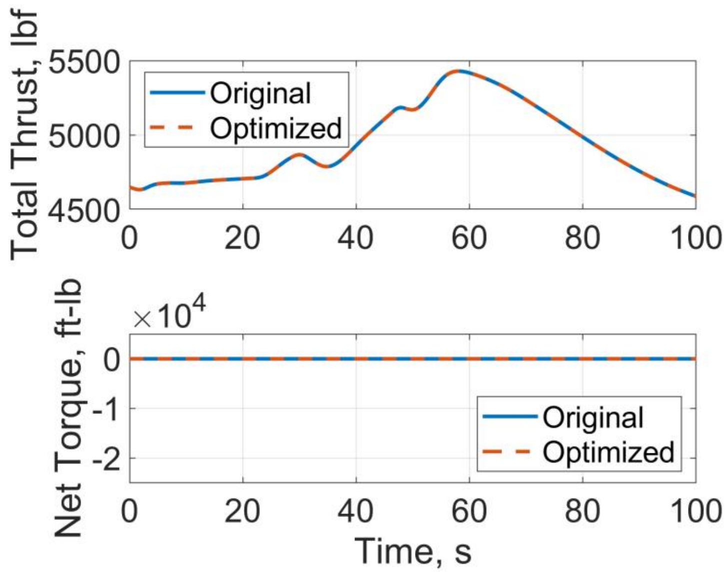
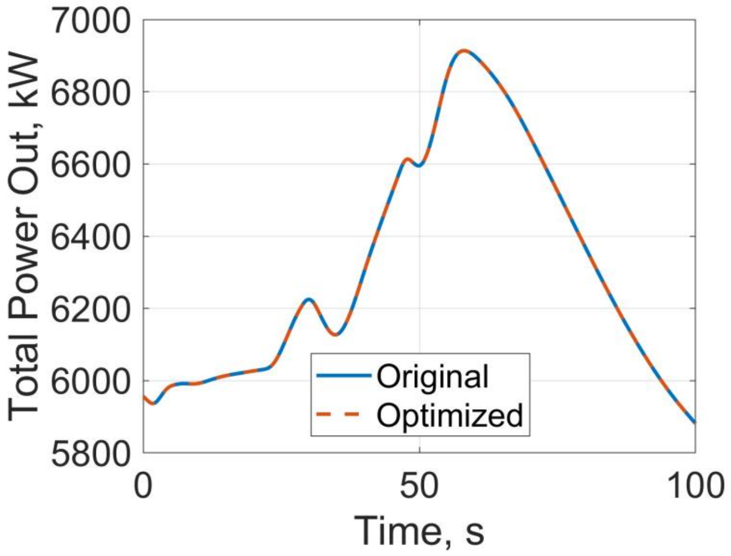
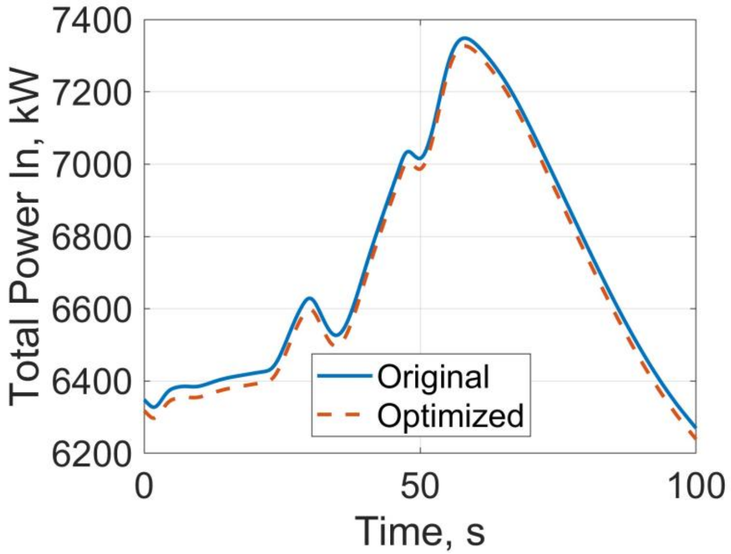
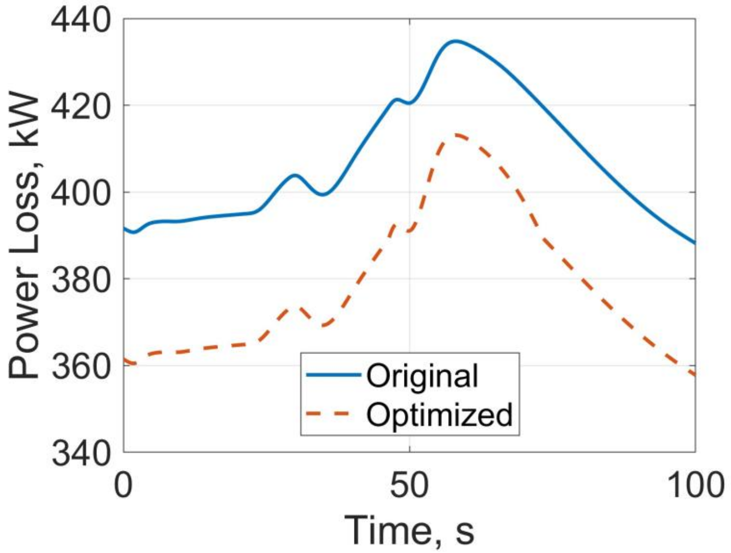


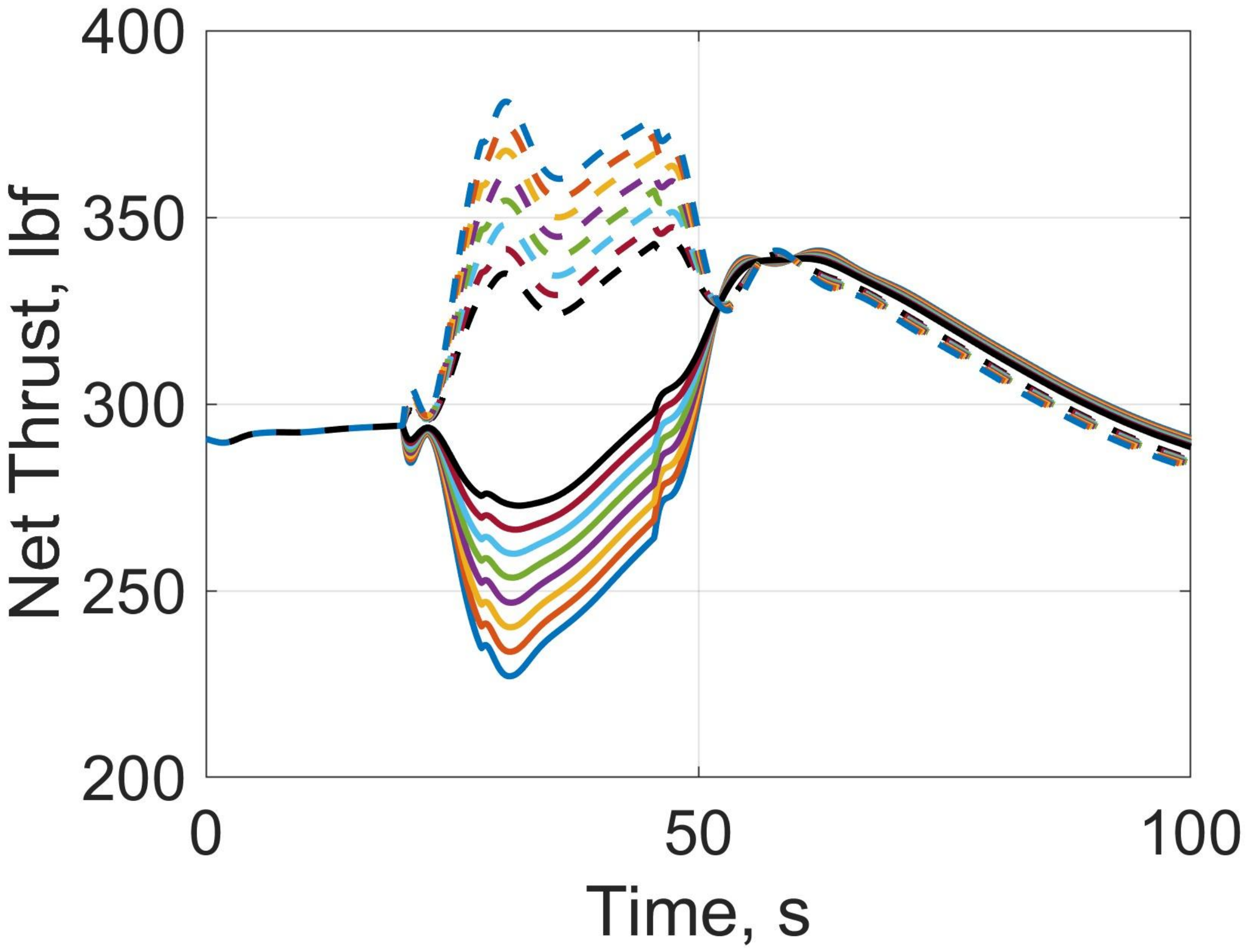






Example 3: Coordinated Turn at Cruise Using Differential Thrust to Replace the Rudder Function

- Baseline fan commands perform a coordinated turn
- Total net thrust profile is the same as in Example 2 but instead of fans moving identically, they move differentially
- Net torque on aircraft varies over time as turn is executed



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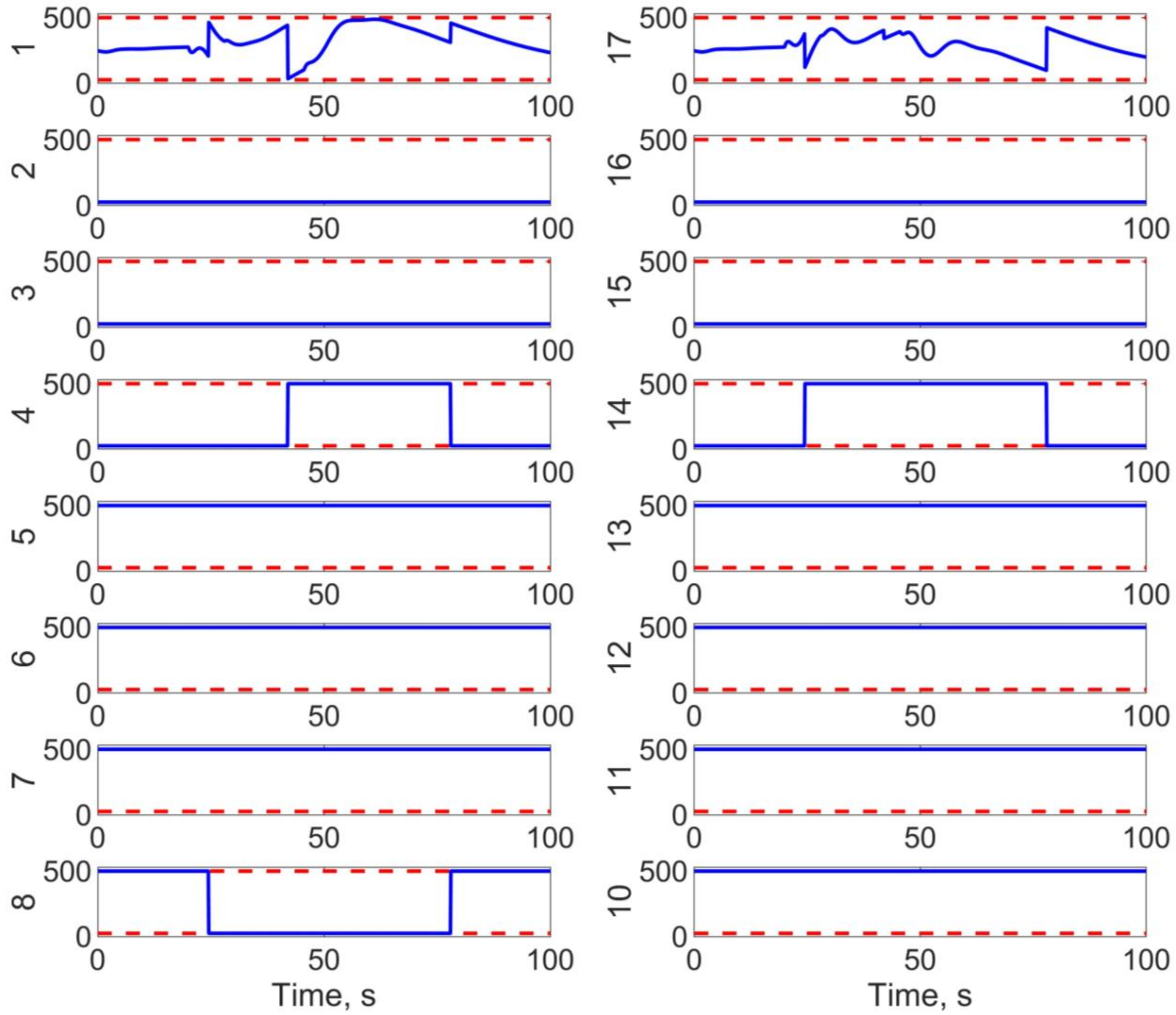

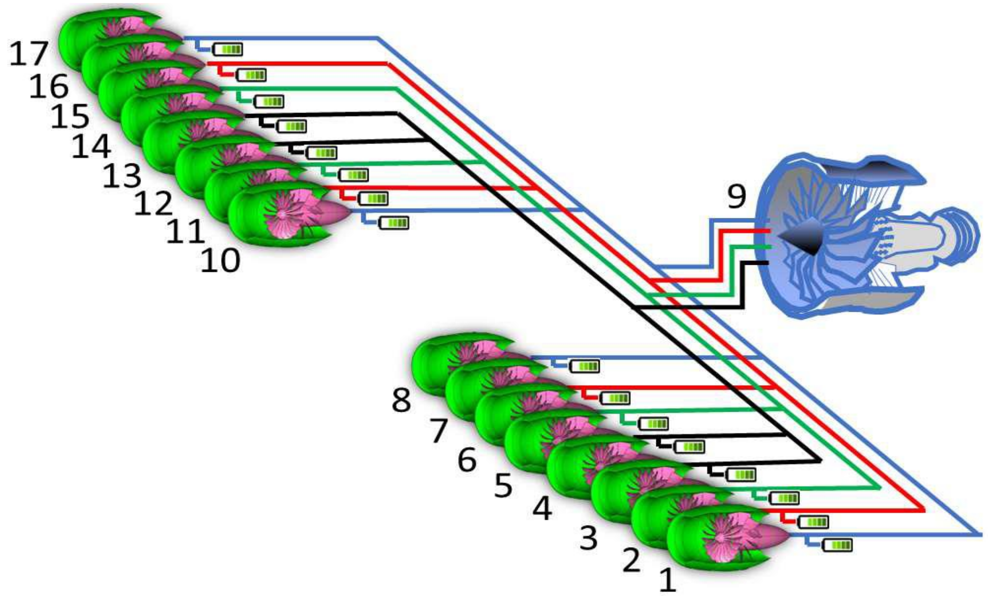

- Fan commands are asymmetric
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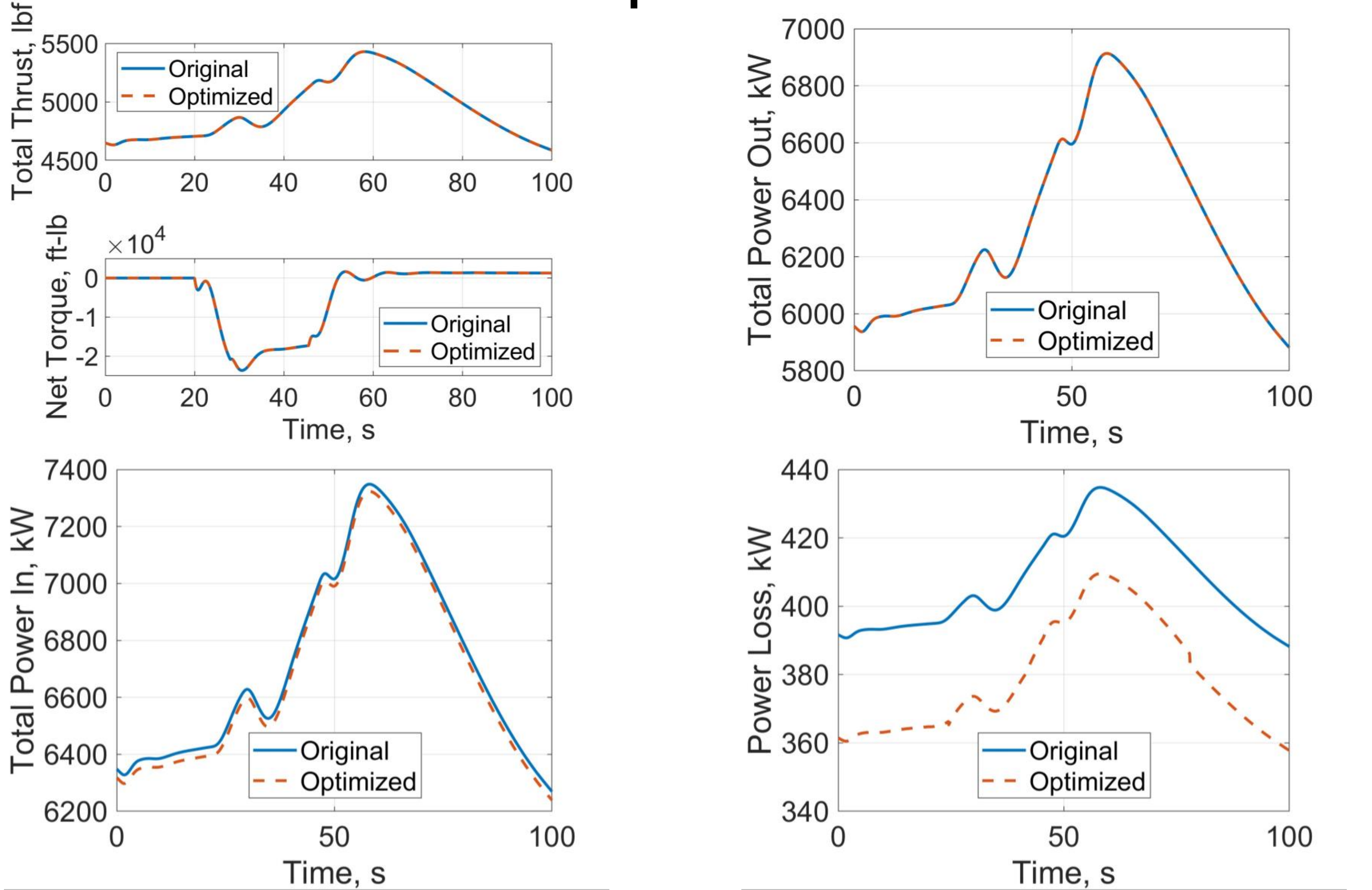
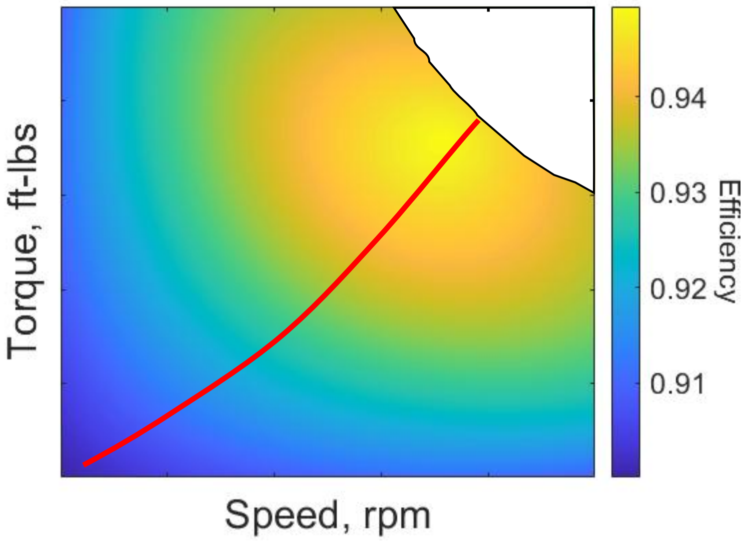
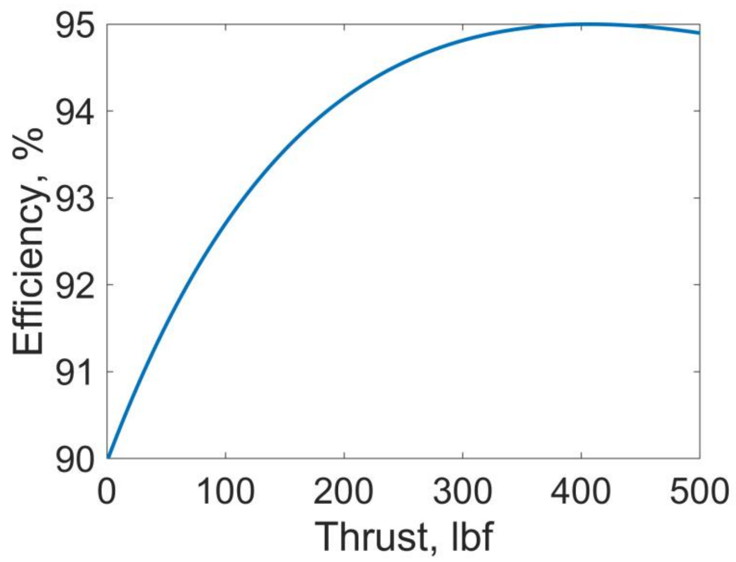


Further Considerations

- Case where peak efficiency is not at power limit
- Efficiency reduces slightly at highest power
- Optimal approach is a case-by-case situation, but operating at a combination of points of lowest and (near) highest efficiency will still often minimize power loss





Conclusions

- The optimal approach presented here is based on reasonable two assumptions
  - The end-to-end powertrain efficiency map has the characteristic of highest efficiency in the high torque/high speed region
  - the efficiency curve can be represented sufficiently well by a monotonically increasing function with decreasing slope
- The resulting bang-bang control scheme, which is not unique, reduces power consumption compared to a smoother control method
- The specific form of the efficiency curve is less important than the general property that it increases monotonically, at least until close to the maximum power boundary, while the slope decreases with increased thrust.
- Overall, the power savings must be weighed against the negative impacts of rapid acceleration and deceleration of the fans—effects such as motor life consumption and the ability of the batteries and bus to support the required power surges
- Slower transitions between operating points for sustained steady state operation can eliminate the undesirable results with a negligible power consumption penalty

Acknowledgments

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