Air-Breathing Propulsion Field Exam
January 2009

This question concerns a ducted propulsor (a fan rotor and stator in a nacelle). The question is broken down into a number of parts, stepping from an initial basic configuration to situations that are more complex. For all parts of the question assume the propulsor is driven by a motor, so you do *not* have to worry about matching with any other turbomachinery and the propulsor and nacelle can be considered lossless and adiabatic.

Part 1) We start with operation in a constant density inviscid fluid, of density ρ. The duct (nacelle) has constant area, A, as in Figure 1. There is a static pressure rise Δp, across the propulsor. The flow at the propulsor exit is axial, i.e., aligned with the axis of the nacelle. The propulsor/nacelle is at static conditions, in other words operating in a fluid that is at rest far away.

1a) What is the axial force exerted by the propulsor on the fluid?
1b) What is the *stagnation* pressure rise across the propulsor?
1c) What are the *static* and *stagnation* pressure distributions along the x-axis, from far upstream to far downstream? Indicate this on the axes in Figure 1.
1d) What is the mass flow through the propulsor?
1e) What is the thrust produced by the propulsor/nacelle combination?
1f) What is the power needed to drive the propulsor?
1g) Is the thrust in item (e) different than the force on the propulsor? If so, where does the "extra force" come from?

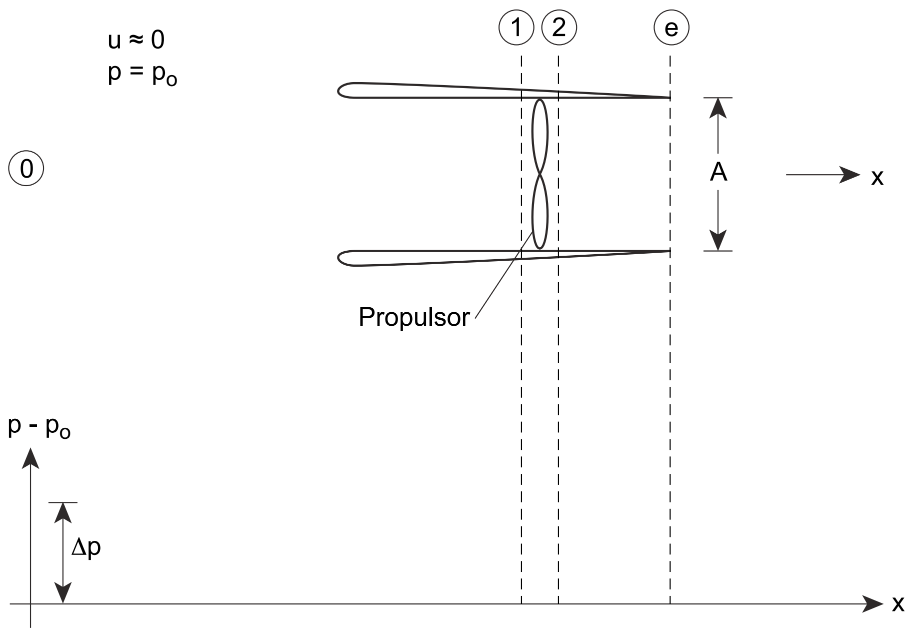

Figure 1: Propulsor in duct.

Part 2) Suppose there is a nozzle downstream of the propulsor, as in Figure 2. The nozzle exit area is A_e, with $A/A_e = 2$. If there is the s*ame* pressure rise, Δp, across the propulsor as there was in Part 1,

2a) What is the pressure, p_2, just downstream of the propulsor?

2b) What is the ratio of mass flow through the propulsor compared to that in part 1?

2c) What are the *static* and *stagnation* pressure distributions along the x-axis, from far upstream to far downstream? Indicate these on the axes in Figure 1.

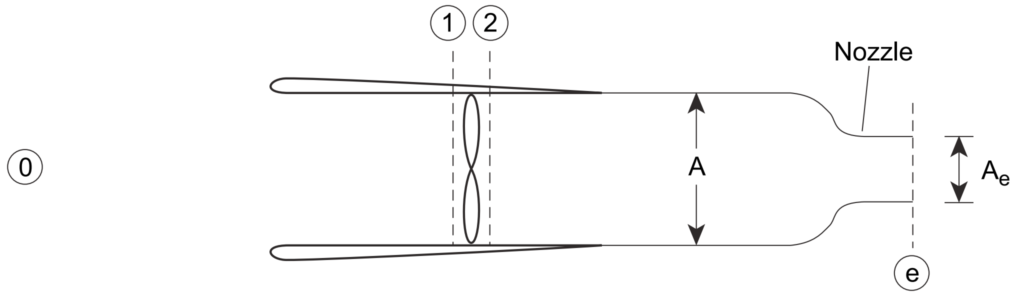

Figure 2: Propulsor with nozzle.

Parts 3 and 4 require qualitative answers only

Part 3) In Part 3 we add two features of the real situation to the configuration of Part 2. First, the propulsor pressure rise is a function of the velocity through the propulsor as indicated in Figure 3. Second, the propulsor/nacelle/throttle is operating at a forward speed of u_0.

3a) What are the *static* and *stagnation* pressure distributions along the x-axis, from far upstream to far downstream? Indicate this on the axes in Figure 1.

3b) If the propulsor operating point at static conditions in Part 2 is denoted by the point *s* on Figure 3, which way does the propulsor operating point move as the conditions change from static to forward speed? Why?

3c) Sketch the streamlines of the flow into the propulsor for the static case and for the forward flight case.

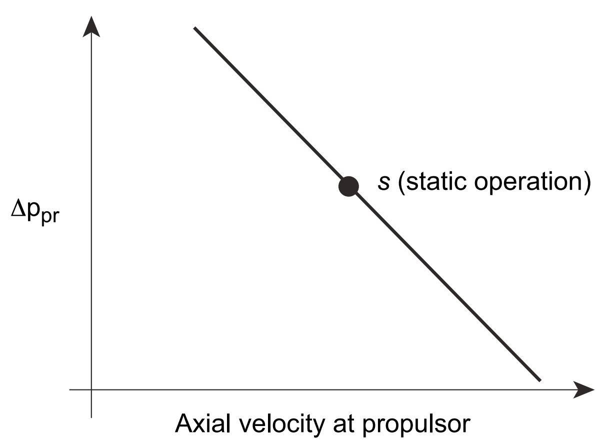

Figure 3: Propulsor pressure rise versus velocity at propulsor.

Part 4) In Part 4 we extend the above considerations to the operation of *propulsors in compressible flow*.

Suppose there are two fans of different design. Each operates in a nacelle as in Figure 4. One is a "conventional fan" of stagnation pressure ratio, fan exit stagnation pressure/fan inlet stagnation pressure, 1.9 at static (take-off) conditions. The second is a geared turbofan with a lower pressure ratio, say 1.4, at static conditions. The nacelles have converging nozzles, with the area of each nacelle defined so that the fan operates at some chosen point at static conditions.

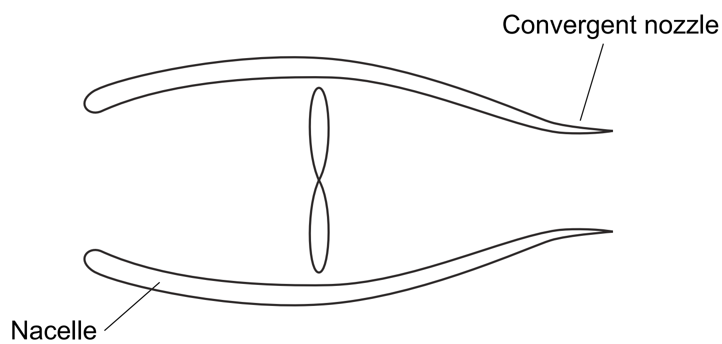

Figure 4: Propulsor-nozzle configuration: convergent nozzle.

The performance of either fan can be represented in terms of stagnation pressure ratio versus corrected flow per unit area, $\dot{m}_c$, for constant corrected speed, as in Figure 5. The static operating point is indicated as *s*. As the aircraft goes to cruise conditions, at flight Mach number, $M_0 = 0.8$, the fan operating point may shift.

Assuming the fans are ideal and that the corrected speed of the fan does not change, for which fan will the shift be greater as the aircraft goes from static to cruise (in other words, for which fan will the mass flow change that occurs be larger)? Why?

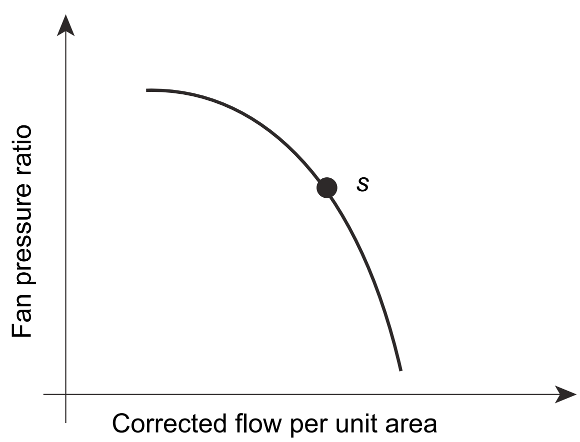

Figure 5: Fan pressure ratio versus corrected flow per unit area.

A complete answer to Part 4 is a sketch of the fan pressure ratio curve for both fans with the static and cruise operating points marked plus explanation of *why* the location of the points is as you have indicated.

Bonus Question

Suppose in a real fan the nozzle area were designed so that that the cruise point is at a best efficiency point. Might this cause any difficulties for operation at static conditions for the low pressure ratio fan? If so, what could they be?