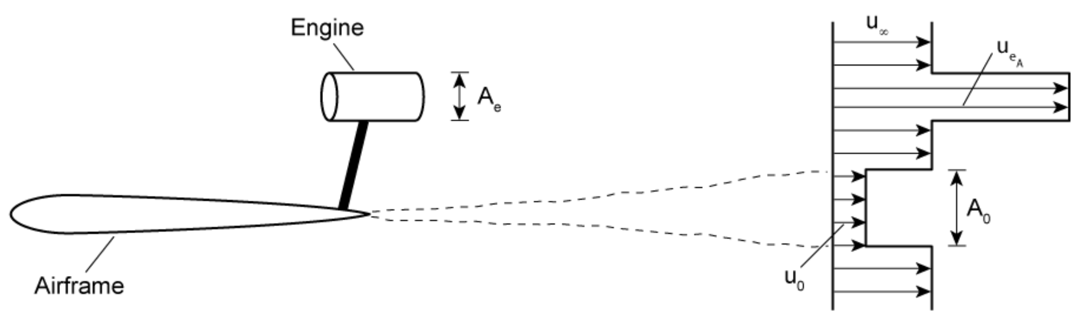
Field Exam: Air-Breathing Propulsion

The Cambridge-MIT 'silent aircraft' has engines embedded in the airframe in order to ingest the airframe boundary layers. The focus of this question is on the possible performance improvement due to this boundary layer ingestion. We will do the problem in steps, starting with a 'conventional' engine configuration. There are thus a lot of separate questions, but do not be daunted by this; it is just a way to separate the different pieces. In addition, for simplicity, please: (i) consider the turbomachinery in the engine to be represented by a fan that is driven by some power source (i.e., don't worry about anything in the engine except the flow through the fan) and (ii) consider only the drag associated with the airframe boundary layers.

A) In case A, below, the engine ingests air at the free stream velocity (the conventional configuration). The fan is ideal (no losses). The flow at inlet and exit of the fan is axial. The fan pressure rise and all relevant velocities in the problem are small enough that the fluid can be considered incompressible throughout, with density ρ. The engine is of constant area, i.e., the flow area is constant from the front of the inlet to the exit, and equal to A_e. The flow exits the engine axially with velocity u_{e_A}. The free stream relative to the airframe has a velocity $u = u_\infty$, and the airframe has a wake with velocity u_0 and wake area A_0. At the downstream location shown the static pressure is uniform and the velocity profile is as indicated at the right of the figure. The aircraft is in steady level flight.

CASE A



In terms of some or all of the parameters $(u_\infty,\ u_0,\ \rho,\ A_0,\ u_{e_A})$:

a) What is the drag of the airframe? (As mentioned, only consider the profile drag on the airframe?)

b) What is the ratio of the engine exit area to the wake area, i.e., what is A_e / A_0?

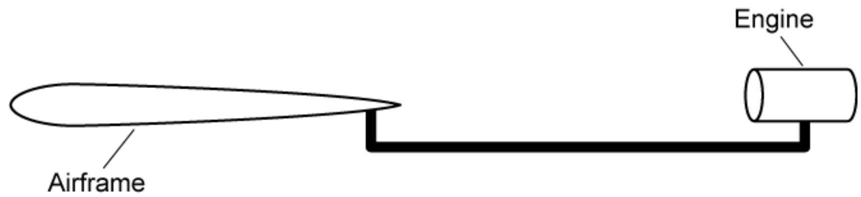
c) What is the stagnation pressure rise across the fan?

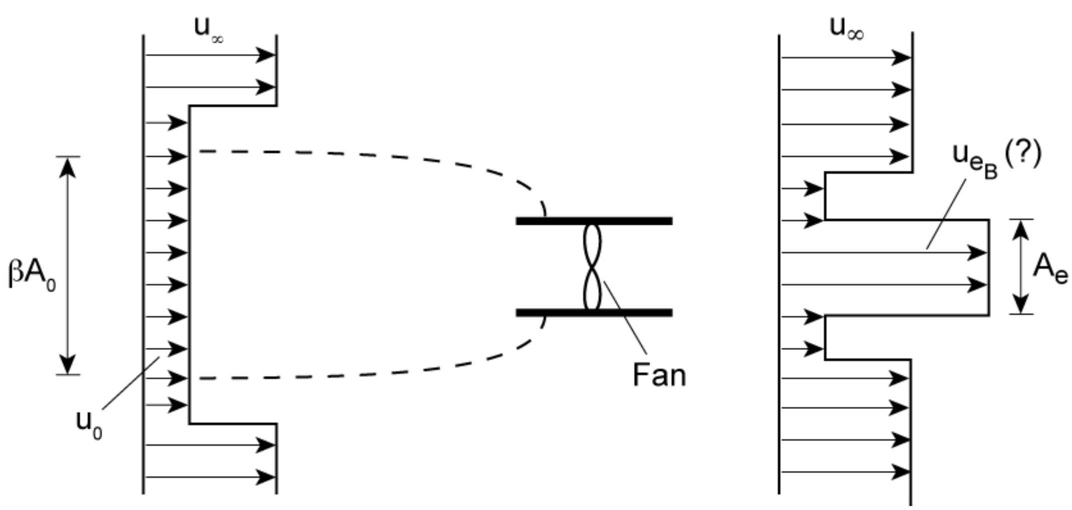
d) What is the static pressure rise across the fan?

e) What is the power input to the fan?

B) In case B, a fraction, β, of the wake fluid is ingested by the engine and goes through the fan. The situation is shown *schematically* below, with the engine placed behind the aircraft to ingest (take in) the wake fluid.   An expanded view of the wake streamlines into the engine and the velocity profiles upstream and downstream of the engine is also given.   The engine can be considered to be far enough downstream so that at the location depicted on the left of the expanded view the static pressure is uniform.

CASE B





Expanded view of ingested wake and fan inside the engine for Case B

For case B, in terms of some or all of the quantities $\left(u_\infty,\ u_0,\ u_{e_B},\ \rho,\ A_0,\ A_e,\ \beta\right)$, not all of which are known as yet,

f) What is the drag of the airframe?

g) What is the thrust of the engine (i.e., the force that is required by the engine to propel the aircraft engine combination at a velocity u_∞?

h) What is the ratio of the exit velocity to the free-stream velocity for case B?   (The result should be able to be expressed in terms of quantities that are either given or have been found in part A, i.e., the exit area is the same as in case A and thus known.)

i) If the numerical value of wake velocity divided by free stream velocity, u_0/u_∞, is 2/3, and *the* ratio of exit velocity *in case A*, divided by free stream velocity, u_{e_A}/u_∞, is 3/2, what is the ratio of exit velocity to free stream velocity, u_{e_B}/u_∞ for case B? Is the mass flow through the engine larger or smaller in case B than in case A?

j) Is the pressure rise across the fan larger or smaller in case B than in case A?

k) Will the power input needed to propel the aircraft at velocity u_∞ be larger or smaller in case B than in case A?

Bonus question: The axial force on the fan is equal to the static pressure rise across the fan. If the static pressure rise is different for cases A and B, can the thrust be the same for the two cases? If so, how does this occur, i.e., how would you explain it physically?