"As the Turbine Turns...."

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Lee S. Langston Professor Emeritus
Mechanical Engineering
University of Connecticut

Some Details of Jet Engine Thrust

Typically, jet airline passengers do not pause to think about it, but part of their ticket purchase is for thrust, the thrust required to fly them to their destination. Jet engine thrust is the force produced by an engine that acts on its aircraft mounts, to pull their plane forward in flight. It is readily measured by load cells when an engine is run in a test stand.

As engineers, some of us have probably been asked by non-engineers to explain how jet engine thrust comes about. The easy answer (but usually not clear to a nontechnical person) is Newton's 2nd Law of Motion for a control volume [1], written in words as

Sum of the Forces = Rate of Production of Momentum. (1)

The jet engine then is a momentum augmenter of the air flow through the engine, to produce a forward force for flight. The momentum flux of the engine exiting flow is greater than that which entered, brought about by the addition of the energy input from combusted fuel, and giving rise to engine thrust.

Interior Forces

One answer I have given to those not versed in Newtonian mechanics is to picture thrust as the summation of all instantaneous forces acting in an axial direction on the surfaces of engine parts exposed to gas flow through the engine. Thrust arises from pressure and frictional forces on these surfaces, e.g., blades, vanes, endwalls, ducts, etc.

This interior force view of thrust is easy to visualize but quite another thing to actually measure. In doing research on secondary flow in gas turbine passages, my former graduate student, Brian Holley (now a researcher at United Technologies Research Center) measured both steady state momentum changes and surface forces, in the much simpler case of a turbine blade cascade [2], shown in Fig. 1.

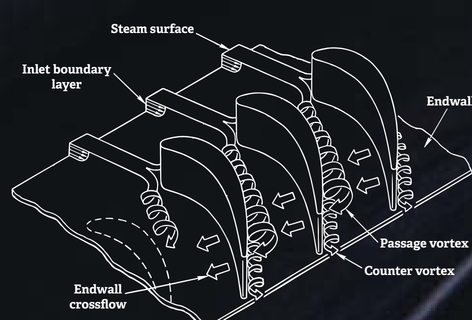

Figure 1. Sketch of a turbine blade cascade with an enhanced rendering of endwall secondary flow [2].

Using a five-hole pressure probe, Brian measured steady state momentum fluxes in and out of the cascade (the right hand side of Eq. (1)) in a few days. The cascade surface pressure forces were measured with an array of pressure taps, and using oil fringe interferometry (OFI), he painstakingly measured frictional surface forces (the left hand side of Eq. 1) which took several months. This yielded a surface force field for checking against CFD calculations, as well as satisfying Eq. (1) within experimental accuracy [3].

I tell the tale to show that measurement of thrust is relatively easily attained by measuring momentum changes, but would be excruciatingly difficult to do by measuring internal surface forces in an engine.

Engine Thrust Anatomy

This sets the stage for using Eq. (1) to calculate the distribution of thrust in a jet engine itself. This will show what part each engine component contributes to net thrust, with some surprises to those of us who might not have gone through such an analysis.

An excellent example of such an analysis is given in the very informative Rolls-Royce publication, *The Jet Engine* [4]. As shown in Fig. 2, the Rolls-Royce example consists of a single spool axial flow turbojet which has a net thrust of 11,158 pounds thrust (lbt), acting to left, for forward flight. (For comparison, most turbofan engines are in the 20,000-30,000 lbt range for single-aisle airliners, and in the 100,000 lbt range for larger airliners.)

The thrust values for each component in the Rolls-Royce single spool engine are shown in Fig. 2. The values (see [4] for details) are calculated from Eq. (1), where the mass

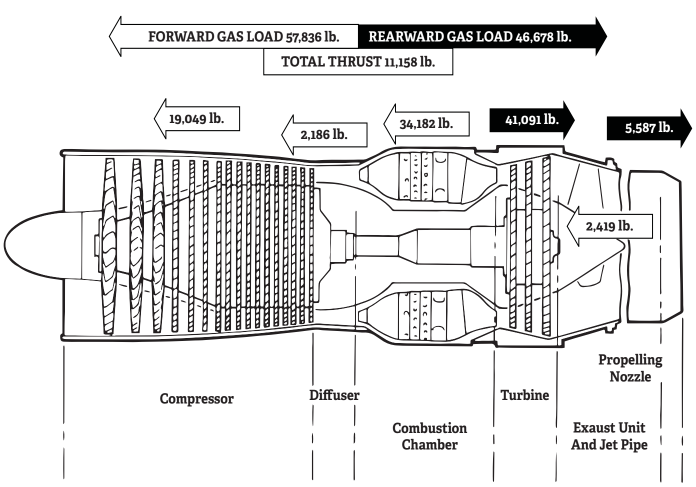

Figure 2. Thrust distribution for a single spool turbojet engine [4].

flow rate, flow areas and pressures are given for each component, and mean one-dimensional flow is assumed in the gas path. Following Fig. 2, an inlet-to-exit analysis yields the following:

1. As shown in Fig. 2, the single spool compressor, with a compression ratio of 7.4, yields a forward thrust of 19,049 lbt (171% of net thrust of 11,158 lbt).

2. From the compressor, gas path flow enters the engine case diffuser, where a pressure gain produces another component of forward thrust of 2,186 lbt (20% of net thrust).

3. Flow from the diffuser enters the combustion chamber, where it is heated at near constant pressure by the combusted fuel, with a large increase in exit flow area. This results in the largest value of forward thrust of any of the engine components, of 34,182 lbt (306% of net thrust).

4. The expanded combustion high temperature gases then enter the turbine (which drives the compressor) where they are accelerated and dropped in pressure and temperature, to produce a rearward thrust of -41,091 lbt (-368% of net thrust).

5. Turbine flow then enters the exhaust unit and jet pipe (Rolls-Royce terminology) where decelerating flow yield a small forward thrust of 2,419 lbt (22% of net thrust).

6. The engine gas flow finally enters the propelling nozzle, to increase its velocity and decrease pressure. As it exhausts to the atmosphere, it produces another rearward thrust of -5,587 lbt (-50% of net thrust).

I invite the reader to sum up the individual component contributions given in Fig. 2 and in items 1-6 above, to yield the net thrust of 11,158 lbt for this Rolls-Royce single spool engine. Newton's 2nd Law of Motion allows us to examine engine component behavior that exhibit both forward and rearward propelling forces, which results in the net trust our airline passengers have purchased.

References

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4. Rolls-Royce, 1996, "Thrust Distribution", The Jet Engine, pp. 207-213.