Maximum Altitude Operations

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The maximum altitude at which an airplane can be flown is limited by three factors:

- Maximum certified altitude.
- Buffet-limited maximum altitude.
- Thrust-limited maximum altitude.

The most limiting of these three altitudes defines the maximum operating altitude. In current Boeing production airplanes, the Flight Management Computer (FMC) determines each of the maximum altitudes, selects the most limiting altitude, and advises the flight crew via the FMC's control display unit (CDU). The flight crew can use this information to determine what flight level changes to accept or request from air traffic control.

It should be noted that the maximum operating altitude is typically *not* the most efficient (in terms of fuel burn) altitude at which to fly. However, it is often not possible to fly at or near the optimum altitude, and flying higher may be preferable to flying lower. The decision to fly at or near the maximum altitude should be made after considering these three different limits and how they affect the airplane.

Maximum Certified Altitude. The maximum certified altitude is a function of the structural capability of the airplane to withstand the pressure difference between the inside of the airplane and the outside air. As the airplane flies higher, the differential pressure exerted on the airplane's structure increases due to the relatively constant cabin altitude and a decreasing outside air pressure. The structure of the airplane (aluminum skins, pressure bulkheads and the associated stringers and frames) bears the load of this differential pressure. The maximum certified altitude is specified in the approved Airplane Flight Manual and ranges from 37,000 feet for the 737-300, -400, and -500 — to 45,100 feet for the 747-400.

Buffet-limited Maximum Altitude. Buffet is caused by the separation of airflow across an airplane's wings (see sidebar below, "Defining Aerodynamic Buffet"). There are generally two types of buffet: high-speed and low-speed. High-speed buffet is caused by supersonic airflow over parts of the wing. When the supersonic air slows to subsonic speeds, a shock wave is formed. This shock wave causes airflow separation, which leads to buffet. Low-speed buffet results from an increase in angle of attack to the point where the airflow separates from the wing. An increase in altitude (at a constant airspeed) or a decrease in airspeed (at a constant altitude) results in an increased angle of attack. Low-speed buffet is associated with loss of lift, or stall — and at high levels is a form of stall warning. In smooth air, the flight crew may be able to detect the onset of buffet during a turn that is within the airplane's certified maneuver capability.

Buffet becomes more limiting when the airplane is in a turn. This is because more lift is required during a bank than would be required for straight-and-level flight. The increased lift is typically expressed in terms of load factor, which is a multiple of gravity (*g*'s). Since the load factor is directly related to bank angle, it defines the maneuvering capability of the airplane. The buffet-limited maximum altitude is the maximum altitude at which an airplane can maneuver to a specified load factor without experiencing a specified level of buffet.

Current production FMCs can be programmed (via maintenance action) with a maneuvering load factor that can be selected from a range of entries. The value entered is normally based on operational policies appropriate to the operator, and defines the buffet-limited maximum altitude for a given gross weight, speed, and center of gravity. In general, the minimum maneuvering load factor entry allowed by the FMC is 1.2 times gravity, or about 34 degrees of bank. This value typically provides a buffet-limited maximum altitude that equals or exceeds the thrust-limited maximum altitude (described below). Values greater than 1.2 can be entered to provide an additional margin to buffet. For airplanes certified by the United Kingdom's Civil Aviation Authority or Europe's Joint Aviation Authorities, the minimum maneuvering capability is required to be at least 1.3 times gravity, or 40 degrees of bank. Further information regarding buffet limits is included in the Airplane Flight Manual and also in Volume 3 of the Operations Manual.

Thrust-limited Maximum Altitude. The third consideration when determining an airplane's maximum altitude capability is the amount of thrust available from the engines. The thrust-limited altitude will vary with the airframe/engine combinations, and is a function of the gross weight of the airplane, its speed, and the outside air temperature. In addition, experience has shown that it is necessary to provide the flight crew with an available thrust margin so they may speed up, climb, or bank the airplane without exceeding the maximum available thrust.

The best operational way to compute the needed thrust margin is to define it in terms of residual rate of climb. The FMC is typically programmed to provide a residual rate of climb of 100 feet per minute at cruise speed, and maximum cruise thrust when

Defining Aerodynamic Buffet

During the course of a flight test program, some parameters must be defined that are not entirely empirical in nature. One of these parameters is the onset of aerodynamic buffet, or "initial buffet," as it is often called.

In earlier flight test programs — until about 1975 — initial buffet was defined literally by the seat of the pilot flying; it was what the pilot actually reported experiencing when he perceived airframe vibration due to buffet. This method, of course, is subject to the differing levels of sensitivity of each of the test pilots, and could lead to data gathering that was not very repeatable.

As Boeing's flight test experience grew, we determined a level of movement at the pilot's seat track that corresponded to approximately the level that triggered the average pilot. This motion is measured by an accelerometer mounted at the pilot's seat track. Today, when the accelerometer readings exceed 0.1 *g* (peak to peak), the condition is defined as initial buffet.

What does this mean to the line pilot? When operating near the maximum altitude predicted by the FMC, it is possible that some pilots will discern small levels of buffet during relatively minor maneuvering. While this condition is somewhat unusual, it represents little cause for concern. Most airlines have a buffet margin programmed into their FMC that is sufficient to ensure a smooth operation during normal maneuvering.

cruising at the thrust-limited maximum altitude. To ensure that the airplane can climb to this altitude at a reasonable rate in the first place, the FMC is typically programmed to provide a residual rate of climb of 300 feet per minute at enroute climb speed and maximum climb thrust during the climb to the cruise altitude. The thrust-limited maximum altitude is the more limiting of the climb and cruise thrust-limited altitudes. As in the case of the maneuvering margin, the current production FMC's residual rate of climb margins can be increased by a maintenance action to provide an additional thrust margin.

The all-engine thrust-limited altitude is not part of the certification basis for an airplane. Therefore, this data does not appear in the Airplane Flight Manual. However, Boeing includes thrust-limited altitude information in our Operations Manuals.

Example

Each airframe/engine combination will have different characteristics for high-altitude operations. These characteristics can be evaluated via the Airplane's Flight Manual and Operations Manual. The following is intended to provide some general information on the type of information you could expect from this analysis.

The 747-400 with Pratt & Whitney 4056 engines at a 0.2 *g* margin to initial buffet is more thrust limited than buffet limited at all but the heaviest gross weights. This airplane will reach its maximum certified altitude only at relatively light gross weights. This means that maximum operating altitude for most operations will be thrust limited.

If a banked turn is initiated at the maximum operating altitude, the thrust limit may be effectively exceeded and the airplane could be forced to slow or descend. Figure 1 shows each of these limits, along with the optimum altitude — for the 747-400 with PW4000 engines.

Summary

The example above illustrates differences in how one airframe/engine combination performs at the maximum operating altitude. Other airframe/engine combinations may exhibit the same, or completely different, maximum altitude performance characteristics. Most operations do not require an airplane to operate at this extreme. However, specific routing considerations and non-normal operations (such as one-engine inoperative cruise) can necessitate flying as high as possible. Flight crews intending to operate at or near the maximum operating altitude should be familiar with the performance characteristics of the airplane in these conditions.

Airlines may wish to review the performance parameters in their airplanes' FMCs to ensure that the maneuver capability and residual rate of climb parameters are consistent with how the flight crews expect the airplane to perform.

If your airline needs assistance with the related analysis, contact Boeing Flight Operations Engineering. The address is shown on page 3 of the *Airliner* Operations Newsletter.

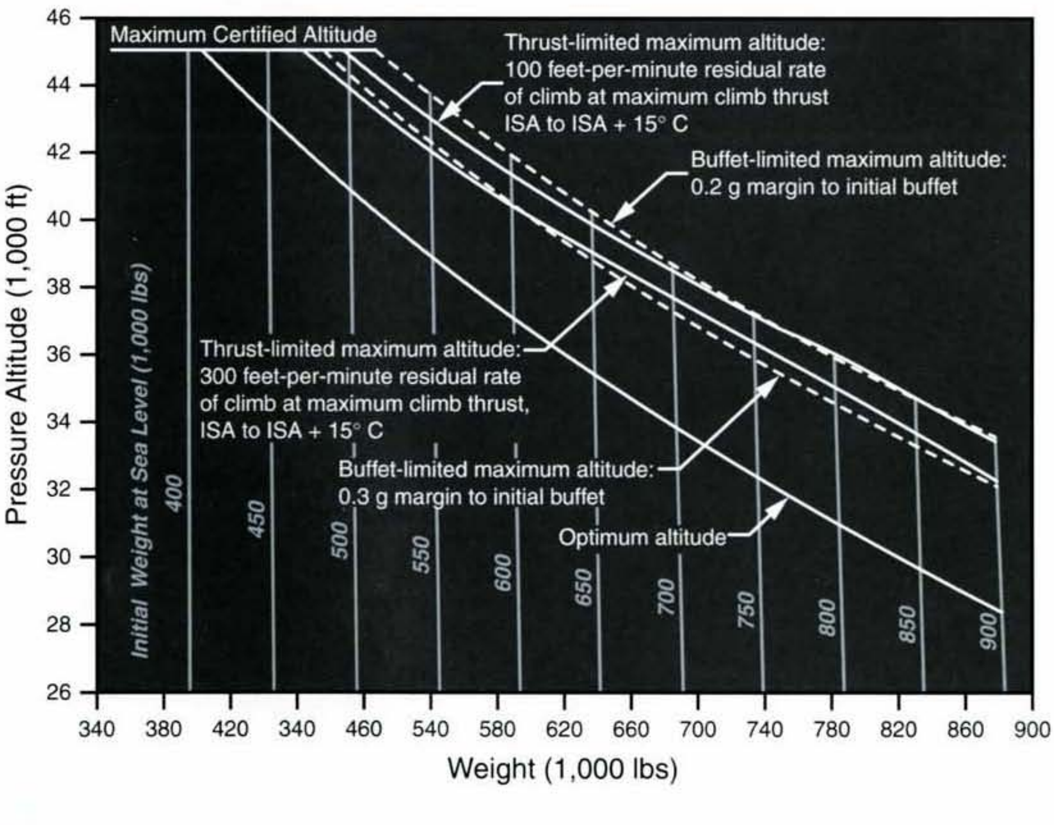

Figure 1. Each airframe/engine combination has different characteristics for high-altitude operations. The example above shows the maximum (and optimum) altitudes for the 747-400 with PW4000 engines.