Engineering Notes

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Approximate Method of Deriving Loiter Time from Range

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Nomenclature

C = specific fuel consumption (fuel flow rate per unit thrust produced)
C_P = power-specific fuel consumption (fuel flow rate per unit power)
E = endurance (loiter time)
L/D = lift-to-drag ratio
R = range
V = velocity
W_f = aircraft final weight (after cruise or loiter mission segment)
W_i = aircraft initial weight (before cruise or loiter mission segment)
η_p = propeller efficiency parameter

Introduction

WITH the advent of the information warfare age, there is a greater need for long-loitering aircraft carrying radars, sensors, communication gear, and the like. Because cost is an always-present constraint, the aircraft platforms for such roles are often converted from other missions such as commercial transportation. In preliminary studies of such conversions, the available loiter time of various platforms is a key parameter for mission feasibility assessment and platform selection. Although range and cruise speed are readily available for most such aircraft, the midmission loiter time usually is not.

This Note describes the derivation and use of a simple relationship between range and endurance based on the Breguet range and loiter equations. Given a known aircraft range and cruise speed, equivalent loiter time can be estimated with reasonable accuracy. In a typical application, this relationship will allow rapid estimation of on-station endurance of commercial aircraft converted to military patrol usage such as antisubmarine warfare or airborne early warning.

Derivation of Method

Jet Aircraft

The Breguet equations are commonly used analytical estimation methods for range and loiter, as derived by Raymer[1] and shown as Eqs. (1) and (2). Equations (1) and (2) assume that the aircraft is allowed to climb slowly as fuel is burned off and weight is reduced (called a cruise climb in the case of range). This is required to maintain the assumption of constant lift coefficient used in their derivation, which also tends to provide the maximum possible range or loiter time.

Range:

$$R = (V/C)(L/D)\ln(Wi/Wf) \tag{1}$$

Endurance:

$$E = (1/C)(L/D)\ln(Wi/Wf) \tag{2}$$

The endurance equation (2) appears to be nothing more than the range equation (1) divided by the velocity. This is trivially obvious from dimensional analysis, and for cruising flight, this division correctly gives you the total flight time over that distance. However, we optimally loiter an aircraft at a lower speed than the speed for best range and so this simple relationship must be adjusted both for aerodynamic, L/D, and propulsion, C, changes due to the differing speed.

In Equation (3), we divide Eq. (1) by velocity. However, Eq. (1) uses L/D and C at cruise conditions, and so we employ ratios to allow usage of loiter conditions:

$$R_{\text{cruise}}/V_{\text{cruise}} = (1/C_{\text{loiter}})(C_{\text{loiter}}/C_{\text{cruise}})(L/D)_{\text{loiter}} \times [(L/D)_{\text{cruise}}/(L/D)_{\text{loiter}}]\ln(Wi/Wf) \tag{3}$$

$$R_{\text{cruise}}/V_{\text{cruise}} = (C_{\text{loiter}}/C_{\text{cruise}})[(L/D)_{\text{cruise}}/(L/D)_{\text{loiter}}] \times \{(1/C_{\text{loiter}})(L/D)_{\text{loiter}}\ln(Wi/Wf)\} \tag{4}$$

or

$$R_{\text{cruise}}/V_{\text{cruise}} = (C_{\text{loiter}}/C_{\text{cruise}})[(L/D)_{\text{cruise}}(L/D)_{\text{loiter}}]\{E_{\text{loiter}}\} \tag{5}$$

In Eq. (4) we have collected terms such that the bracket at the right is now the desired endurance E, with aerodynamic and propulsion terms under loiter conditions [Eq. (5)]. Solving for this loiter time gives

$$E_{\text{loiter}} = (R_{\text{cruise}}/V_{\text{cruise}})/\{(C_{\text{loiter}}/C_{\text{cruise}})[(L/D)_{\text{cruise}}/(L/D)_{\text{loiter}}]\} \tag{6}$$

Now we need to estimate those propulsion and aerodynamic ratios from cruise to loiter conditions.

The change in speed from cruise to loiter changes the aircraft lift-to-drag ratio because it changes the lift coefficient. It can be theoretically shown[1] that a jet loiters optimally at its speed for best L/D, whereas it cruises optimally at a higher speed. At this higher speed, the aircraft is flying at a condition where the ratio $C_L^{1/2}/C_D$ is maximized. This higher speed results in an L/D that is reduced to 0.866 of the optimal L/D. (The aircraft goes further, nonetheless, because of the higher speed.) Here

$$(L/D)_{\text{cruise}} = 0.866(L/D)_{\text{loiter}} \tag{7}$$

Substituting this into Eq. (6) gives

$$E_{\text{loiter}} = 1.16(R_{\text{cruise}}/V_{\text{cruise}})/(C_{\text{loiter}}/C_{\text{cruise}}) \tag{8}$$

This can be used for jet aircraft where the engine fuel consumption data under cruise and loiter conditions is known (propeller-powered

Received 17 January 2003; revision received 7 February 2003; accepted for publication 9 February 2003.

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aircraft, discussed next). For most jet engines, the specific fuel consumption C is slightly improved at the lower speeds of loiter. However, throttle setting is reduced for loiter, which for many jet engines results in an increase in fuel consumption so that perhaps the change in specific fuel consumption can be ignored, resulting in

$$E_{\text{loiter}} = 1.16(R_{\text{cruise}}/V_{\text{cruise}}) \tag{9}$$

which is an approximation for most jets. Obviously, consistent units must be employed, such as range in nautical miles and speed in knots, resulting in loiter time in hours.

A check of this method for jets was made using the Boeing E-6A, for which range and endurance data is publicly available.[2] The range is 6350 n mile with a 455-kn cruising speed. Its total endurance is given as 15.5 h, and its endurance at 1000 n mile radius from base is 10.5 h. When the range and speed data are used, endurance is calculated as follows.

E-6A maximum endurance (hours):

$$E = \frac{1.16(6350)}{455} = 16.2$$

E-6A endurance at 1000 n mile (hours):

$$E = \frac{1.16(6350 - 2000)}{455} = 11.1$$

These are close but optimistic by 4.5 and 5.7%, respectively. Calculations for several other transport-class jets indicates similar optimism, possibly due to practical aspects of engine operation under loiter conditions.

A caveat is given: These equations and rules of thumb assume loitering at the same altitude as the cruise was done. A better loiter may be obtained at a lower altitude. However, other real-world factors ignored in this method seem to ameliorate/obliterate this effect.

Propeller-Powered Aircraft

For a propeller-powered aircraft, the thrust obtained from the propeller reduces with velocity while the actual fuel consumption of the engine remains essentially constant. Therefore, the thrust specific fuel consumption is degraded substantially with increased velocity. One can develop a version of each Breguet equation using the engine's power-specific fuel consumption C_P by substitution into Eqs. (1) and (2), as provided in Eqs. (10) and (11). (For derivation see Raymer.[1]

Propeller range:

$$R = (\eta_p/C_p)(L/D)\ \ell\text{n}(Wi/Wf) \tag{10}$$

Propeller endurance:

$$E = (\eta_p/VC_p)(L/D)\ \ell\text{n}(Wi/Wf) \tag{11}$$

where η_p is the propeller efficiency parameter equal to thrust power obtained divided by engine power employed.

To determine available loiter time given range, we can start with the loiter equation (11) and employ ratios to permit usage of the L/D and velocity from cruise conditions, again collecting terms. The bracket at the right in Eq. (13) is the range [see Eq. (10)], with aerodynamic and propulsion terms under range conditions:

$$E_{\text{loiter}} = (\eta_p/C_p)(1/V_{\text{cruise}})(V_{\text{cruise}}/V_{\text{loiter}})(L/D)_{\text{cruise}} \times [(L/D)_{\text{loiter}}/(L/D)_{\text{cruise}}]\ \ell\text{n}(Wi/Wf) \tag{12}$$

$$E_{\text{loiter}} = (V_{\text{cruise}}/V_{\text{loiter}})[(L/D)_{\text{loiter}}/(L/D)_{\text{cruise}}](1/V_{\text{cruise}}) \times \{(\eta_p/C_p)(L/D)_{\text{cruise}}\ \ell\text{n}(Wi/Wf)\} \tag{13}$$

$$E_{\text{loiter}} = (V_{\text{cruise}}/V_{\text{loiter}})[(L/D)_{\text{loiter}}/(L/D)_{\text{cruise}}]\{R_{\text{cruise}}/V_{\text{cruise}}\} \tag{14}$$

Note that the power-specific fuel consumption C_P is assumed to change little with speed. Also, we have assumed that propeller efficiency is essentially unchanged from cruise to loiter. This is a good assumption provided that the aircraft has variable pitch propellers and that it is not cruising at such a speed that there are substantial losses due to tip-Mach effects. Should either of these be substantially nonconstant, the method can be adjusted to include ratios from cruise to loiter conditions.

We now need to estimate the velocity and L/D ratios. It can be theoretically shown[1] that propeller-powered aircraft cruise optimally at their best L/D speed, but loiter slower at 76% of cruise speed. At this lower speed, the aircraft is flying at a condition where the ratio $C_L^{3/2}/C_D$ is maximized. This loiter speed yields, in an accidental show of analytical symmetry, a loiter L/D that is 0.866 times the cruise, that is, optimal, L/D. Substituting these ratios into Eq. (14) yields

$$E_{\text{loiter}} = 1.14\{R_{\text{cruise}}/V_{\text{cruise}}\} \tag{15}$$

which is an approximation for most propeller aircraft. This 14% increase is close but not identical to the differently derived 16% increase for a jet if the change in specific fuel consumption C is neglected.

A check of this method for propeller-powered aircraft used the General Atomics Predator, which has 24 h of loiter at 434 n mile radius and a quoted maximum endurance of 40 h. Using Eq. (15) with the Predator best cruise speed of 70 kn gives a predator endurance (hours) of

$$E = \frac{1.14(868)}{70} = 14$$

Adding this to 24 h gives 38 hours, 5% less than the quoted value.

As another test, a notional piston-propeller light twin previously designed by this author for optimization research[3] was evaluated. This design has an as-drawn takeoff gross weight of 2200 lbs (998 kg) and a span of 29 ft (8.8 m). With use of the RDS-Professional aircraft design and analysis computer program as-drawn range is calculated to be 2585 n mile at a best speed of 140 kn. Using this simplified method gives a calculated loiter time of 21 h vs a refined loiter calculation of 20 h (giving a 5% error). Thus, the notional light twin endurance (hours) is

$$E = \frac{1.14(2585)}{140} = 21$$

A turboprop has substantially more variation in fuel consumption with velocity than a piston-propeller. To assess this, the Grumman E-2C Prowler was considered. Its range is given[2] as 1394 n mile at 268 kn, and endurance is 6 h. By this method we get for the E-2C endurance (hours)

$$E = \frac{1.14(1394)}{268} = 5.9$$

This indicates that perhaps even a turboprop aircraft can be approximated by the described propeller method. Because the jet equation is slightly overpredicting endurance in our test cases, it is suggested that the 1.14 constant be used for jets as well.

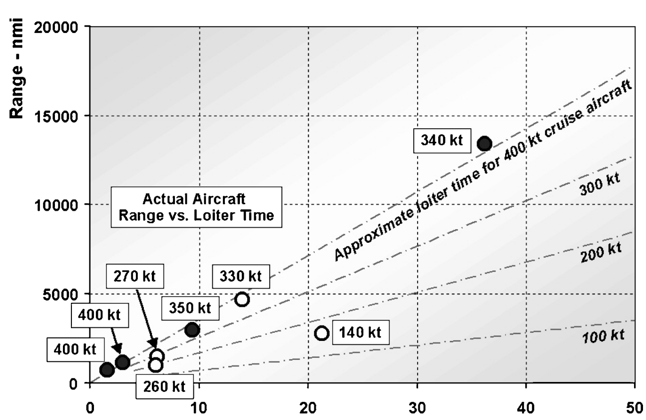

Fig. 1 Actual aircraft range and loiter plotted against approximation results: ●, jets and ○, propeller aircraft.

Figure 1 shows the range and endurance of a number of aircraft plotted vs the approximation of Eq. (15) for various cruise speeds. Aircraft shown include the F/A-18, P-3, S-3, Global Hawk, Harrier, E-2C, and C-2, selected because both range and loiter information are available in public sources.[2] Also included is the notional light twin described earlier. Figure 1 shows a fairly good correspondence, with the given data points lying fairly near their equivalence line for their cruise speed.

The only exception is the Global Hawk. (See data point with greatest range and loiter.) Global Hawk flies at extreme altitude, where its maximum speed and its stall speed are almost the same, and so it cannot slow down for more optimal loiter. Its loiter time is just slightly greater than range divided by cruise speed, without the 14% adjustment suggested herein.

Summary

A relationship between range and endurance was derived, based on the Breguet range and loiter equations. Given a known aircraft range and the cruise speed, equivalent loiter time can be estimated by a simple and useful rule of thumb: Loiter time equals range divided by cruise velocity, increased 14%.

Despite different derivations, this approximation can be used for both jets and propeller aircraft. Checks of this method were made that seem to indicate reasonable prediction of loiter time based on publicly available data, with results typically within 5% of the correct values.

References

[1]Raymer, D., *Aircraft Design: A Conceptual Approach*, 3rd ed., AIAA, Washington, DC, 1999.

[2]Taylor, J., *Jane's All the World Aircraft*, Jane's, London, 2000.

[3]Raymer, D., "Enhancing Aircraft Conceptual Design using Multidisciplinary Optimization," Ph.D. Dissertation, Dept. of Aeronautics, Swedish Royal Inst. of Technology, Stockholm, May 2002.

Viscous Flow Solutions over CN-235 Cargo Aircraft

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Introduction

THE cost of predictions from computational fluid dynamics (CFD) is continually decreasing relative to costs associated with wind-tunnel experiments. Flow solutions computed with CFD codes present detailed flowfield information, which might be too expensive to obtain in a wind tunnel. Consequently, CFD methods are becoming more popular and are being used for complementing experimental studies to decrease the number of wind-tunnel measurements. Aircraft companies rely heavily on the CFD methods in the preliminary design of a new aircraft or in the modification of an existing one.

Table 1 Aircraft model data

Parameter	Value
Overall length, m	21.353
Full span, m	25.81
Root chord, m	3.0
Wing mean chord, m	2.62
Wing gross area, m	59.1
Wing incidence angle, deg	3
Wing airfoil	NACA65$_3$-218
Horizontal and vertical tail airfoils	NACA64$_1$-012

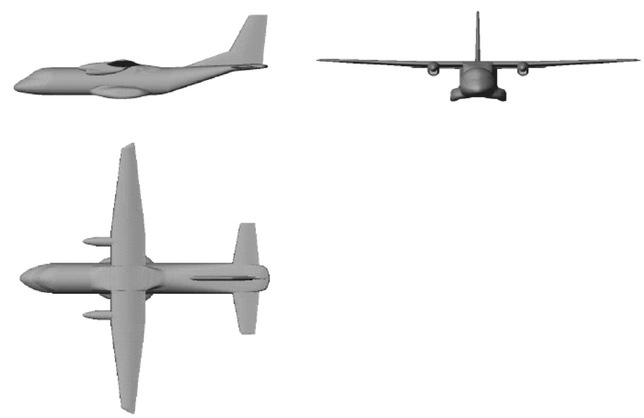

Fig. 1 Aircraft model geometry.

The CN-235 aircraft (Fig. 1 and Table 1) is a twin turboprop tactical transport aircraft having a maximum cruising speed of 455 km/h (Ref. 1). It was initially designed and built through cooperation between Construcciones Aeronuticas SA (CASA) of Spain and Dirgantara Indonesia (IPTN). Later, CASA developed its own versions.

It has been built by Turkish Aerospace Industries (TAI) of Turkey under production license by CASA for several years. It has a reputation for mission versatility, minimum support requirements, and reliable operation in a wide range of environments. It has been modified for both civilian and military purposes, and has gained civil certification by safety bodies in many countries. Modified versions of the aircraft are in military service in more than 20 countries, including Turkey.

In the past, CFD methods have been employed for the aerodynamic analysis of the CN-235 aircraft. Karaagac[2] used Advanced Aircraft Analysis (AAA) software[3] (ver. 2.2) to compute the aerodynamic characteristics of the CN-235 aircraft. AAA is based on empirical methods for airplane design, airplane flight dynamics and automatic flight controls, and airplane aerodynamics and performance. It is widely used for preliminary design, stability, and control analysis of a new and existing airplane. Bahar et al.[4] obtained inviscid flow solutions for CN-235 aircraft using the CFD-FASTRAN flow solver[5] (ver. 2.2) with unstructured grids. Kurtulus recently computed viscous and inviscid flows over CN-235 at cruise, landing, and takeoff conditions using the VSAERO software (ver. 6.2),[6,7] which is a panel-based potential flow solver with viscous–inviscid interactions.

In this study, viscous flows over CN-235 cargo aircraft are computed at cruise conditions and at angles of attack ranging from 0 to 5 deg by the use of the CFD-FASTRAN Navier–Stokes solver. Computations are performed on a Pentium III-based personal computer with a 1-Gb memory. Grid sensitivity and verification studies are performed on the clean-wing configuration (Fig. 2). Inviscid and viscous flow solutions with available turbulence models over the full aircraft are compared at a range of incidence angles. Computed lift and drag values are also compared with semi-empirical and numerical data available in the literature. It is shown that viscous flow solutions provide valuable aerodynamic data, which may

Received 7 April 2003; presented as Paper 2003-3661 at the 21st Applied Aerodynamics Conference, Applied computational aerodynamics with validation, Orlando, FL, 23 June 2003; revision received 22 January 2004; accepted for publication 23 January 2004.

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