Engineering Notes

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A Method of Computing Indicated Airspeed in Ground Effect

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Nomenclature

A = aspect ratio
C_{Di} = induced drag coefficient
C_L = lift coefficient
e = airplane efficiency factor
K_1 = lift distribution factor
K_2 = wing twist factor
P_S = static pressure, psf
P_T = total pressure, psf
q = dynamic pressure, psf
V = true airspeed, fps
V_C = calibrated airspeed, fps
V_I = indicated airspeed, fps
V_R = resultant true airspeed, fps
W = downwash velocity, fps
h/b = altitude/wing span
"V" = lift distribution factor
"W" = wing twist factor
α = angle of attack, deg
δ = flap deflection angle, deg
π = 3.14159
ρ = density, slugs/ft^3
λ = taper ratio

Subscripts

FLAPS = flaps deflected
GE = in ground effect
∞ = out of ground effect
o = sea-level conditions

THE effect on the airspeed system due to flying near the ground is an increase in pressure measured by the static port. This increase in pressure is due to a decrease in downwash when flying at less than 1 wing-span distance above the ground. A decrease in downwash yields a smaller induced angle of attack, thus decreasing the magnitude of the resultant velocity past the static port. Since the measured total pressure will be the same,

$$P_T = P_{S_\infty} + q_\infty = P_{SGE} + q_{GE}$$

where P_{SGE} and q_{GE} are measured conditions rather than true conditions. Solving for q_{GE} yields

$$q_{GE} = P_{S_\infty} - P_{SGE} + q_\infty = (1 - K)P_{S_\infty} + q_\infty$$

Since pressure is inversely proportional to velocity squared, assume that $(1 - K)$ is proportional to

$$\Delta\ [1/(V_{RGE}/V_{R\infty})^2] = \Delta(V_{R\infty}/V_{RGE})^2$$

$\Delta(V_{R\infty}/V_{RGE})^2$ is defined as

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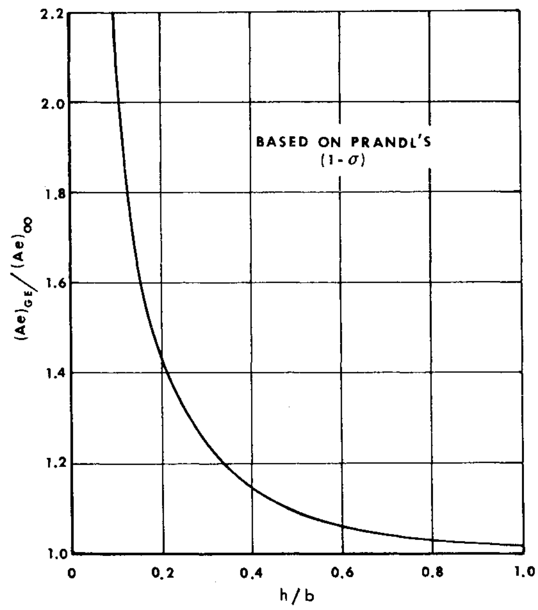


Fig. 1 Apparent aspect ratio in ground effect.

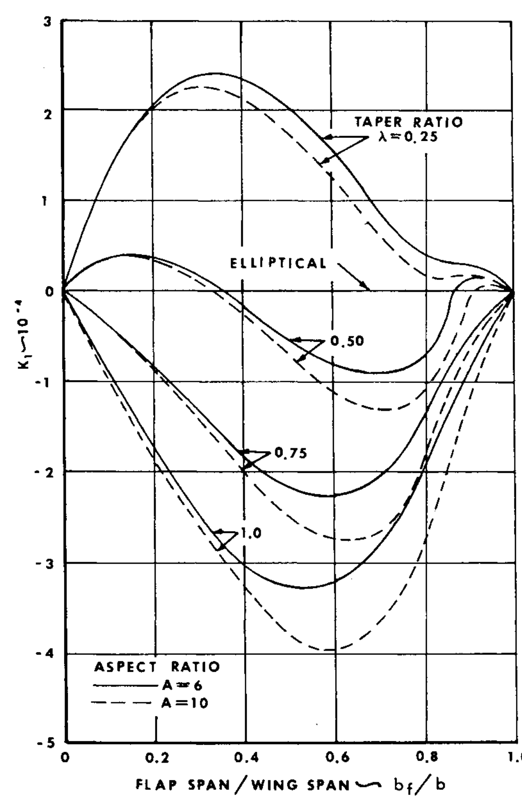
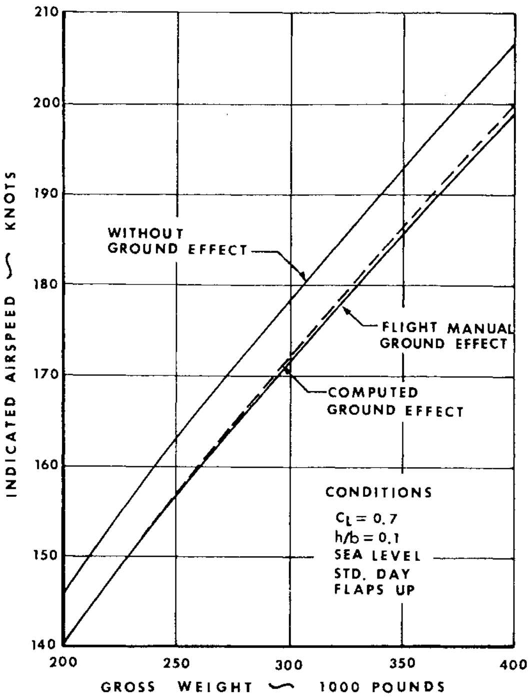
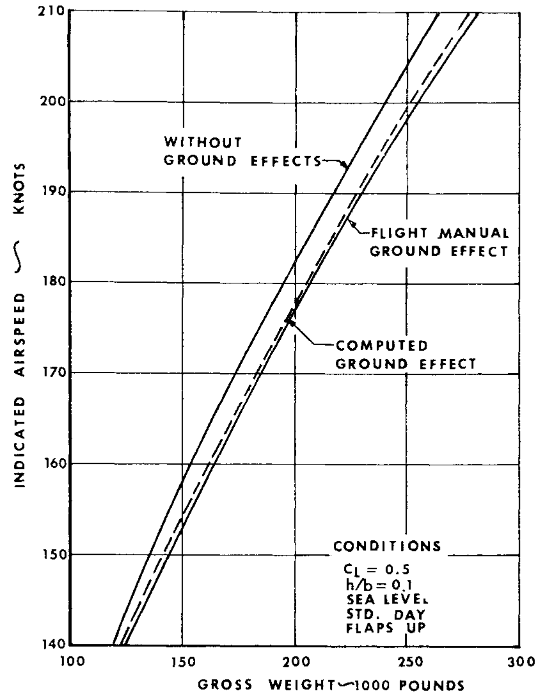


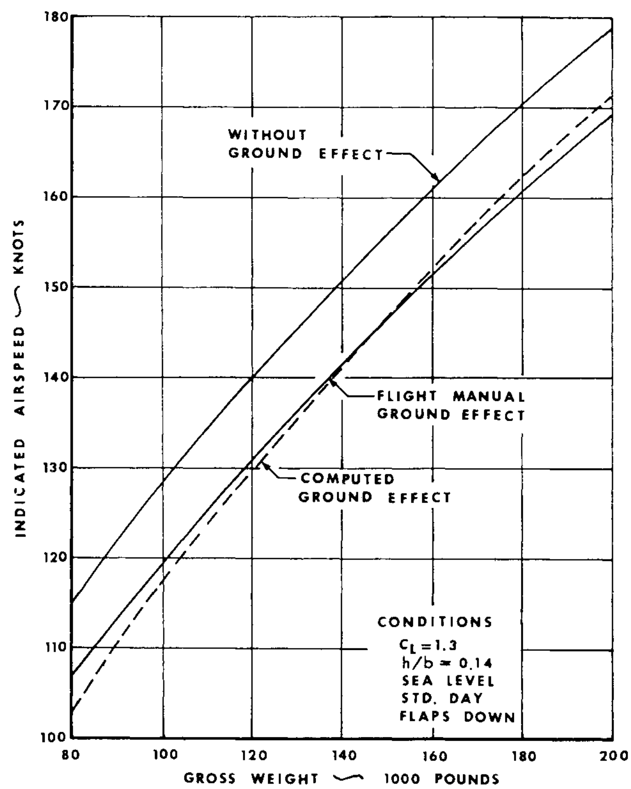
Fig. 2 Variation of lift distribution due to deflected flaps.



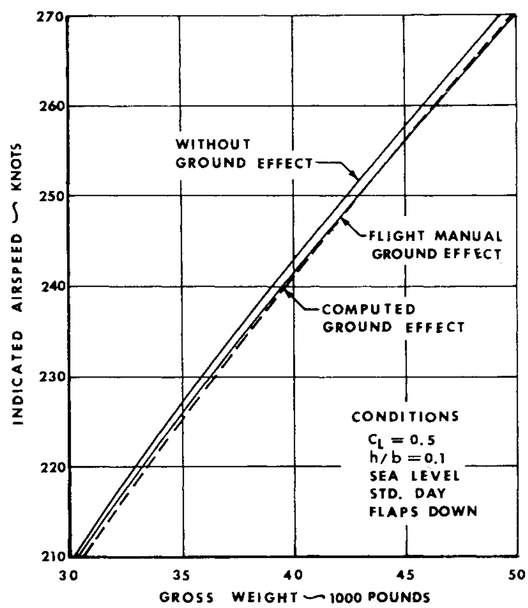
a) B-52H



b) KC-135



c) RB-47



d) F-101B

Fig. 3 Ground effects.

$$\Delta\left(\frac{V_{R\infty}}{V_{RGE}}\right)^2 = \frac{V^2 + W_\infty{}^2 - (V^2 + W_{GE}{}^2)}{V^2 + W_{GE}{}^2} = \frac{V^2 + W_\infty{}^2}{V^2 + W_{GE}{}^2} - 1$$

Therefore $q_\infty - q_{GE}$ is proportional to $[(V^2 + W_\infty{}^2)/(V^2 + W_{GE}{}^2) - 1]P_{S\infty}$.

From here we must determine the constant of proportionality. The decrease in downwash corresponds to an increase in aspect ratio. This is not a physical increase but an apparent increase. For an elliptical lift distribution $A_\infty < A_{GE}$. For a nonelliptical lift distribution Ae will also change due to ground effect. Hence $(Ae)_\infty < (Ae)_{GE}$. This change is presented in Ref. 1 and is shown here in Fig. 1. Assume that the constant of proportionality is equal to $(W_\infty/W_{GE})^2$. Then

$$\left(\frac{W_\infty}{W_{GE}}\right)^2 = \left(\frac{C_L V}{\pi A e}\right)^2_\infty \Big/ \left(\frac{C_L V}{\pi A e}\right)^2_{GE} = \frac{(Ae)_{GE}{}^2}{(Ae)_\infty{}^2} = C^2$$

and $W_{GE} = W_\infty/C$. This then yields

$$q_\infty - q_{GE} = C^2[(V^2 + W_\infty{}^2)/(V^2 + W_{GE}{}^2) - 1]P_{S\infty}$$

Solving for V_{GE},

$$V_{GE} = \left\{\frac{2}{\rho}\left[-C^2\left(\frac{V^2 + W_\infty^2}{V^2 + W_{GE}^2} - 1\right)P_{S_\infty}\right] + V^2\right\}^{1/2}$$

For sea-level standard day conditions, $V = V_C$ and

$$V_{IGE} = \left\{\frac{2}{\rho_0}\left[-C^2\left(\frac{V_C^2 + W_\infty^2}{V_C^2 + W_{GE}^2} - 1\right)P_0\right] + V_C^2\right\}^{1/2} + V_{P_\infty}$$

where V_{P_∞} is the flaps up static source correction out of ground effect. Experience has shown that indicated airspeed is nearly constant with altitude for altitudes from sea level to 10,000 ft. Therefore, indicated airspeed in ground effect will be nearly constant for low altitudes.

A similar equation may be developed for airplanes with flaps deflected by taking into account the change in induced drag due to flap deflection. The induced drag of wings with deflected partial-span flaps consists of three components:

$$C_{D_i} = (C_L^2/\pi Ae) + \text{"}v\text{"}C_L\Delta C_L + \text{"}w\text{"}(\Delta C_L)^2$$

where $\Delta C_L = (d\alpha/d\delta)\delta(dC_L/d\alpha)$ and indicates the two-dimensional increment of the lift coefficient in those wing parts that are equipped with flaps. Numerical values for "V" and "W" are presented in Ref. 2. An approximate equation for C_{D_i} may be found by assuming average values for the various constants involved.[1] Thus, assuming $d\alpha/d\delta = 0.5$ and $dC_L/d\alpha = 0.1$ the induced drag coefficient is found to be in the order of

$$C_{D_i} = (C_L^2/\pi Ae) + K_1C_L\delta + K_2\delta^2$$

where δ is in degrees.

For rectangular or tapered wings $K_2 \approx 2.3 \times 10^{-6}$ for flap-span ratios between 0.3 and 0.55. The K_1 factor (indicating a variation of the lift distribution along the span) is a function of the wing-plan form. Numerical values of K_1 may be obtained from Fig. 2. K_1 is positive for triangular wings (having zero taper ratio). This means that upon deflecting inboard flaps, the concentration of lift in the center part is increased. K_1 is negative for rectangular wings; their lift distribution is brought nearer the elliptical optimum by deflecting flaps.

We can now evaluate the constant of proportionality for the flaps down case. Downwash will be

$$(W_\infty)_{\text{FLAPS}} = W_\infty + K_1\delta V + (K_2\delta^2V/C_L)$$

Therefore

$$\left(\frac{W_\infty}{W_{GE}}\right)^2_{\text{FLAPS}} = \left[\frac{W_\infty + K_1\delta V + K_2\delta^2V/C_L}{W_{GE} + K_1\delta V + K_2\delta^2V/C_L}\right]^2$$

The flaps down equation then becomes

$$(V_{GE})_{\text{FLAPS}} = \left\{\frac{2}{\rho}\left[-\left(\frac{W_\infty + K_1\delta V + (K_2\delta^2V/C_L)}{W_{GE} + K_1\delta V + (K_2\delta^2V/C_L)}\right)^2 \times \left(\frac{V^2 + [W_\infty + K_1\delta V + (K_2\delta^2V/C_L)]^2}{V^2 + [W_{GE} + K_1\delta V + (K_2\delta^2V/C_L)]^2} - 1\right)P_{S_\infty}\right] + V^2\right\}^{1/2}$$

and for sea-level standard day conditions,

$$(V_{IGE})_{\text{FLAPS}} = \left\{\frac{2}{\rho_0}\left[-\left(\frac{W_\infty + K_1\delta V_C + (K_2\delta^2V_C/C_L)}{W_{GE} + K_1\delta V_C + (K_2\delta^2V_C/C_L)}\right)^2 \times \left(\frac{V_C^2 + [W_\infty + K_1\delta V_C + (K_2\delta^2V_C/C_L)]^2}{V_C^2 + [W_{GE} + K_1\delta V_C + (K_2\delta^2V_C/C_L)]^2} - 1\right)P_0\right] + V_C^2\right\}^{1/2} + (V_{P_\infty})_{\text{FLAPS}}$$

where V_{P_∞} is the flaps down static source correction out of ground effect. This indicated airspeed is also good for altitudes from sea level to 10,000 ft. The method presented here has been evaluated for representative aircraft of various types. The method correlates very well with flight test data. Figures 3a–3d are representative examples.

References

[1] Hoerner, S. F., "Fluid Dynamic Drag," published by the author, 1965, pp. 7-1–7-14.

[2] Pearson, H. A. and Anderson, R. F., "Calculation of the Aerodynamic Characteristics of Tapered Wings With Partial-Span Flaps," TN665, 1939, NACA.

Impact of Air-Breathing Propulsion System Developments on Test Facilities

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Introduction

THE past three or four years have shown a resurgence of interest in the further development of air-breathing propulsion systems. This resurgence has introduced rapid developments in flight propulsion as well as manufacturing and testing, thus causing an acute problem—test facility obsolescence. This note discusses the trends in subsonic, supersonic, and hypersonic propulsion and the problems related to developing test facilities for them.

Large Subsonic Engines

The continuing growth of commercial air travel, air-freight cargo, and military transport requirements are responsible for stimulating the improvement of large subsonic transport engines. Major advances are needed in lower total-noise levels, lower propulsive specific fuel consumptions, higher take-off and cruise thrusts, lower specific weights, and lower maintenance costs. The high-bypass-ratio turbofan engine has emerged as the best over-all compromise to meet these varying demands.

One of the major costs in providing development facilities is the simulation of the environmental atmosphere in which the engines must operate, both at sea level and altitude. Figure 1 shows the general trend of engine airflow requirements. The growth of this important facility parameter has been enormous and is due to the shift from straight turbojet engines to high-bypass-ratio turbofans. This type of engine, with still larger airflows, will play a prominent role in subsonic flight of the future.

There are two main reasons to expect that the growth in required airflow will continue. The first is the continued growth of required thrust. The second is the economic requirement for lower flight specific fuel consumption. To meet these requirements the designer has been forced to put the energy output of the core engine into larger and larger fan airflows, thus accounting for the major increase in required airflow which has taken place in recent years.

The basic problems encountered by the engine manufacturer in developing these fan engines are over-all noise level generated by the engine, engine life and reliability, and development of and the accurate determination of the required installed performance of the engine.

Much fundamental work is being done on the noise problem. Efforts are directed at both the origin of the noise and at

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