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AEROSPACE INFORMATION REPORT

AIR 781

GUIDE FOR DETERMINING ENGINE STARTER
DRIVE TORQUE REQUIREMENTS

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1. PURPOSE:

The purpose of this report is to provide a general guide to the factors utilized and the methods employed in determining turbine starter torque and engine pad strength requirements.

2. SCOPE:

A general discussion is presented herein, to outline the starter functions which are necessary for a successful engine start. In addition, sample calculations are included to illustrate an accepted method of determining the engine starting time from known data. Further consideration is then given to the relationship between starter torque output and engine pad strength and a generalized formula is presented for calculating the theoretical transient torque peaks for a simplified starter-engine system. Sample calculations for actual tests are included, and the results of these calculations are compared with measured values.

3. DISCUSSION:

3.1 Starter Functions:

Figure 1 pictorially illustrates the torque versus speed characteristics of a typical starter on an assumed jet engine. In general, the starter must provide sufficient torque to accelerate a jet engine, including its accessories, up to its firing speed and to continue supplying torque assist until the engine is developing sufficient torque to rapidly accelerate itself to idling speed. Path a-b on the engine torque curve of Figure 1 represents the drag torque imposed by friction, windage, and pumping losses of the engine and its accessories, with engine ignition occurring at point b. Path b-c-d occurs after engine ignition, with net drag torque still present from b to c and with net engine output torque being supplied from c to d. The starter should be designed to cutout (point f) within a finite speed range which is dependent upon the engine's characteristics. Idle speed is designated as point d on the engine torque curve and, although stabilized engine idle occurs at zero net torque output, the point of idling is represented as shown to depict a condition where the aircraft power lever has been set for a higher speed range. This assumption is made purely for the purposes of providing a standard for starting time calculations which is not affected by the various types of fuel control scheduling utilized to approach the stabilized idle condition.

Referring again to Figure 1, it can be seen that curve e-g represents the net torque for the engine-starter system, i.e., the algebraic summation of the engine and starter torques. The shaded area under this curve then becomes a measure of the net energy available for engine acceleration up to cutout speed. Application of this available energy to the calculation of engine starting time is covered in the following section.

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3.2 Calculation of Starting Time to Engine Idle:

Since one of the important considerations used in selecting a starter for an aircraft engine combination is the time lapse between start initiation and attainment of engine idle, it appears desirable to discuss a method of determining this time lapse. Following is the derivation for the acceleration time formula:

From dynamics we have: $T = I_m \alpha = I_m \frac{d\omega}{dt}$

Where: T = Net torque in lb ft
 I_m = Equivalent system mass moment of inertia at starter shaft in slug ft²
 α = Angular acceleration in radians/sec²
 ω = Angular velocity in radians/sec
 t = Time in seconds

Since $\omega = \frac{2\pi N}{60}$ where N = Speed in rev./min. at starter drive

$$\frac{d\omega}{dt} = \frac{\pi}{30} \frac{dN}{dt}$$

$$\text{Therefore } T = \frac{\pi I_m}{30} \frac{dN}{dt}$$

$$\text{or } t_{\text{idle}} = \frac{\pi I_m}{30} \int_0^{N_{\text{idle}}} \frac{dN}{T} \quad (1)$$

From this equation the time to engine idle can be determined by:

$$\Delta t = \frac{\pi I_m \Delta N}{30 T_{\text{av}}} \quad (2)$$

Where ΔN = any speed increment along curve e-g of Figure 1.

T_{av} = average net torque along curve e-g for the speed increment ΔN

Δt = acceleration time increment for speed increment ΔN

Using equation (2) along the entire length of curve e-g and summing the resultant time increments will then give the time to engine idle, the accuracy of this method increasing with the number of increments taken.

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3.2.1 Sample Calculation for Starting Time:

Starting time to stabilized engine idle speed for the typical engine-starter combination depicted in Figure 1 is calculated as follows:

Starter equivalent inertia measured at shaft = .900 slug ft²

Engine equivalent inertia at starter drive = 16.3 slug ft²

$$I_m = 16.3 + .9 = 17.2 \text{ slug ft}^2$$

From Figure 1 we obtain average net torque at each increment of speed.

ΔN	T_1	T_2	T Av. Net Torque
0-200	425	408	417
200-400	408	383	396
400-600	383	360	372
600-800	360	330	345
800-1000	330	292	311
1000-1200	292	250	271
1200-1400	325	307	316
1400-1600	307	292	299
1600-1800	292	280	286
1800-2000	280	269	274
2000-2200	269	262	265
2200-2400	262	257	259
2400-2600	257	257	257
2600-2800	257	262	260
2800-3000	262	273	268
3000-3200	273	290	281
3200-3400	175	232	203
3400-3600	232	295	263
3600-3800	295	370	332
3800-4000	370	450	410

Substituting in equation (2)

$$\Delta t_1 = \frac{\pi I_m \Delta N}{30 T} = \frac{\pi (17.2)(200)}{30 T} = \frac{360}{T} = \frac{360}{417} = .863$$

$$\Delta t_2 = \frac{360}{396} = .909$$

$$\Delta t_7 = \frac{360}{316} = 1.14$$

$$\Delta t_3 = \frac{360}{372} = .968$$

$$\Delta t_8 = \frac{360}{299} = 1.204$$

$$\Delta t_4 = \frac{360}{345} = 1.043$$

$$\Delta t_9 = \frac{360}{286} = 1.26$$

$$\Delta t_5 = \frac{360}{311} = 1.158$$

$$\Delta t_{10} = \frac{360}{274} = 1.314$$

$$\Delta t_6 = \frac{360}{271} = 1.329$$

$$\Delta t_{11} = \frac{360}{265} = 1.359$$



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$$\Delta t_{12} = \frac{360}{259} = 1.39$$

$$\Delta t_{17} = \frac{360}{203} = 1.773$$

$$\Delta t_{13} = \frac{360}{257} = 1.40$$

$$\Delta t_{18} = \frac{360}{263} = 1.369$$

$$\Delta t_{14} = \frac{360}{260} = 1.385$$

$$\Delta t_{19} = \frac{360}{332} = 1.084$$

$$\Delta t_{15} = \frac{360}{268} = 1.343$$

$$\Delta t_{20} = \frac{360}{410} = .878$$

$$\Delta t_{16} = \frac{360}{281} = 1.282$$

$$\Sigma \Delta t = 23.578 \text{ seconds starting time}$$

3.3 Determination of Transient Torque Peaks:

A typical starter torque versus speed curve is depicted on curve e-f of Figure 1. This curve represents the steady state torque characteristics, assuming stabilized values of torque and speed. During actual operation, however, the starter torque output will be reduced by the product of acceleration and the starter moment of inertia. Figure 2(a), is an actual recording of torque versus time. For a clear illustration of impact torque a running re-engagement cycle is depicted, where high pressure air is introduced to the stationary starter turbine while the starter output shaft and flywheel load are coasting at a constant speed. The highest transient torque occurs when the clutch engages, shortly after the speed of the starter turbine side of the overrunning clutch reaches the speed of the output shaft. Figure 2(b) and (c) show the relationship between output speed and time and starter inlet pressure and time respectively, for the same running re-engagement cycle. As shown on Figure 2(a), the maximum transient torque is 540 pound feet, while the steady state torque is approximately 200 pound feet. For this particular example therefore, the ratio of transient impact torque to steady state torque is approximately 2.70 to 1. It is this impact torque factor which is of paramount importance in the determination of engine pad strength and matching of the starter to the engine.

To date the strength of most engine starter pads and drives has been dictated by drawing AND20002 which, for Type XII-S and -T accessory pads, specifies:

"For turbojet engines the drive shall be capable of withstanding the maximum torque equal to 2.0 times the constant torque required for a fifteen (15) second starting period beginning from rest and ending at drive speed S. For turboprop engines the drive shall be capable of withstanding the maximum torque equal to 2.0 times the constant torque required for a twenty five (25) second starting period beginning at rest and ending at drive speed S."

Knowing the engine torque characteristics and the starting time requirement, the engine manufacturer can then calculate the required constant torque and the corresponding shaft strength.

Although the resultant energy level is indicative of that required for a successful start, the assumption of constant starter torque output is not valid since all current starters have torque outputs which decrease with increasing speed. For equal energy levels therefore, the torque at 0 rpm must be higher than the calculated constant torque and the drive strength should be increased accordingly. From this it is apparent that the slope of the starter torque curve should be considered in determining the engine drive strength.

The impact torque factor was selected as 2.0 in drawing AND20002; but since this factor varies with different engine-starter combinations, a more accurate determination should be established. Accordingly, the following section presents a theoretical derivation of an equation relating steady state and impact torque, engine and starter inertia and torsional stiffness, and system backlash.

3.3.1 Theoretical Considerations:

The torque driving system of an engine-starter combination can generally be simplified as shown on Figure 3. For this system:

I_s = starter equivalent mass moment of inertia

I_e = engine equivalent mass moment of inertia

k_s = starter torsional spring constant

k_e = engine torsional spring constant

Two other factors having a measurable effect on the impact torque factor are:

α = the relative angle of rotation between I_s and I_e from the time when I_s and I_e have equal velocities to the time of clutch engagement. (This represents clutch play and gear and spline backlash in the actual system).

T = Steady state starter torque. Theoretically, this is the indicated torque, but since this value is usually not known, the brake torque output may be used with little error.

Assuming that the engine is not changing speed, that there is no damping in the system, and that the engine-starter system can be simplified as shown on Figure 3, an equation for impact torque can be derived as follows:

Assuming θ_s = angular position of I_s

θ_1 = angular position of starter clutch half

θ_2 = angular position of engine clutch half

θ_e = angular position of I_e

$\theta_s = \theta_1 = \theta_2 = \theta_e = 0$ at the time of engagement