11th ANKARA INTERNATIONAL AEROSPACE CONFERENCE **AIAC-2021-030**
8-10 September 2021 - METU, Ankara TURKEY

MILITARY TURBOFAN ENGINE STARTING SYSTEMS AND DETERMINATION OF ENGINE STARTING TIME

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ABSTRACT

Turbofan engines are widely-used as main propulsion system solution on fixed-wing military air vehicle platforms. There are various methods to start these type of engines, and those starting system alternatives are introduced first in this paper. Then, Air Turbine Starting System (ATSS) is proposed for starting a low by-pass turbofan engine which is installed on fixed-wing military air vehicle platform. Architecture of the system and main components are illustrated, and working principle is explained. An analytical calculation method for engine starting time determination is presented, and basic inputs for this analysis and their resources are specified. Since aircraft and other systems' data are sensitive to share, numeric values are not given on the result plots. As a consequence of the analysis, engine starting capability of starting system is evaluated, and starting time is determined in various operational conditions. Finally, compliance of results is assessed against general aviation specifications.

INTRODUCTION

Engine starting systems are utilized in order to start and ensure self-sufficiency of main propulsion system. For this purpose, ground support equipment or air vehicle installed secondary power systems can be used. The essential duty of engine starting system is to ensure quick and reliable engine start.

As principle, torque extracted from engine starter is served to overcome engine internal friction, provide required torque to drive integrated accessories, assist air intake pumping into the engine, and then remaining excessive torque is used to accelerate engine main shaft to rotational speed where engine can sustain itself without starter assistance.

Common Starter Types and Basic Features

Starter/Generator: This equipment is mainly used on relatively small engines. Latest studies estimate that Starter/Generator's (S/G's) may be feasible for larger engines in the future [Society of Automotive Engineers, 2004]. This equipment gets its initial energy from aircraft battery. After engine starting process, S/G mode change takes place, and this equipment serves as electrical generator in order to feed aircraft systems' electrical demands.

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Figure 1: Starter/Generator overview

Jet Fuel Starter: Jet Fuel Starter (JFS) is a small gas generator that is installed on Airframe Mounted Accessory Drive (AMAD) directly. After start command, JFS works in a jet engine Brayton cycle principle, and JFS drives its pad on AMAD via output shaft. Then, this mechanical energy is transmitted to Power Take-Off (PTO) shaft. PTO shaft is connected to engine via a gear train, and engine HP spool is rotated by this energy. The most prominent usage of JFS is on F-16 aircraft. Since the energy source, JFS, is installed directly on AMAD, this starting method constraints versatility and brings installation issues.

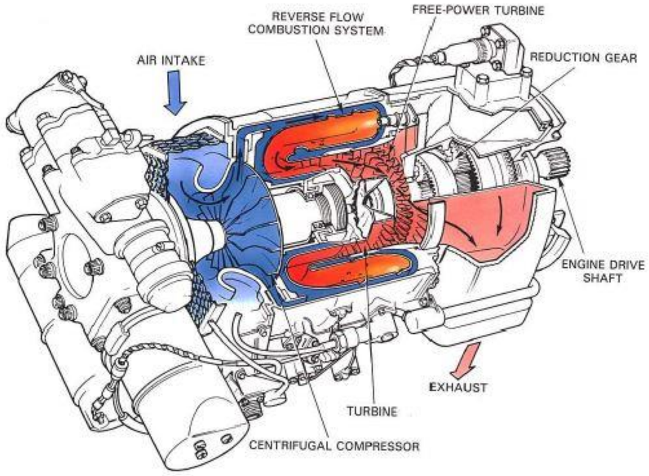

Figure 2: Cross section of Jet Fuel Starter [Rolls Royce plc, 1996]

Air Turbine Starter: Air Turbine Starter (ATS) is the most common type of starters in the field. Basically, it is composed of turbine disk, reduction gearbox, and optional clutch assemblies for AMAD engage-disengage. Some ATS configurations contain its own internal lubrication systems whereas other configurations use AMAD shared lubricating oil.

This type of engine starting system is called as Air Turbine Starting System (ATSS), and ATSS is composed of ATS and related pneumatic valves installed on piping. APU is small gas turbine engine working in Brayton cycle principle, and it is the primary bleed air source for ATSS. In addition to APU bleed air, ground support equipment bleed air and engine cross bleed from opposite engine for twin-engine air vehicles can be used as ATSS bleed air source.

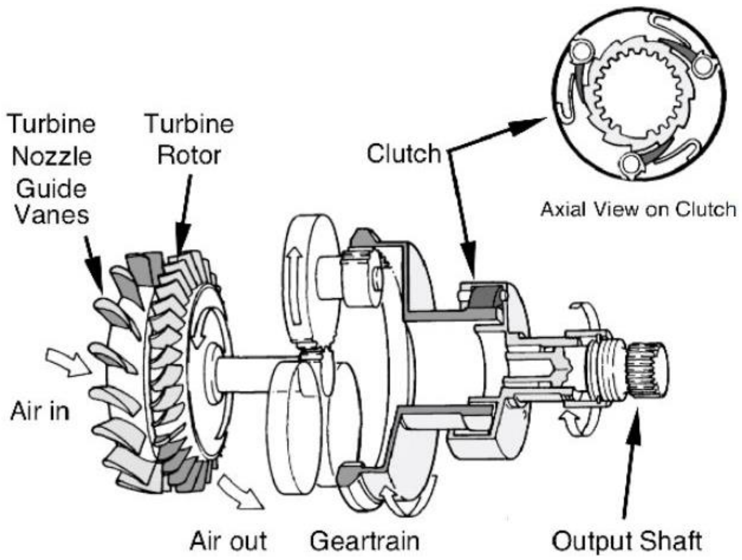

Figure 3: Main components of Air Turbine Starter [Linke-Diesinger, 2008]

Working principle of ATSS is to convert pneumatic energy to mechanical energy. Bleed air coming from Auxiliary Power Unit (APU) or other sources drives ATS turbine disc, and generated torque is transmitted to AMAD via reduction gearbox. Here, high speed low torque is converted to low speed high torque by reduction gearbox. Then, this torque is transferred to PTO shaft, and torque is applied to engine HP spool via gear train between engine and PTO shaft. During ATS operation, ignition is turned on by moving throttle to idle position when firing speed is reached. After that, starter assist continues until the engine attains its self-sustainability. When the engine is self-sustaining, clutch mechanism provides starter cut-off from AMAD.

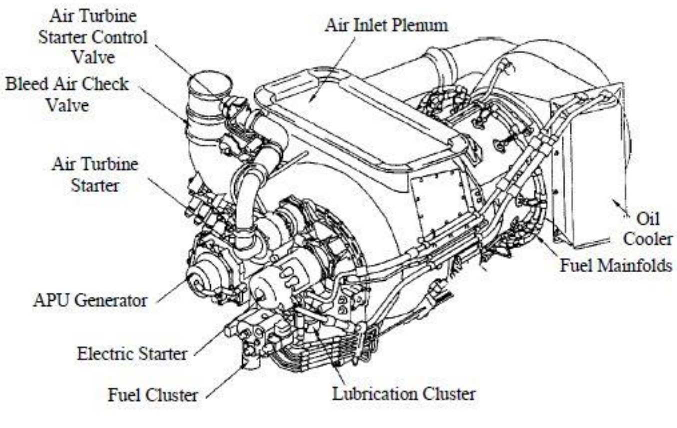

Figure 4: Auxiliary Power Unit overview [Moir and Seabridge, 2008]

In this paper, ATSS is proposed as engine starting system for twin-engine military air vehicle, and methodology for engine starting system analysis is explained.

METHOD

System Architecture

Basic architecture of ATSS type engine starting system for twin-engine military air vehicle is defined as;

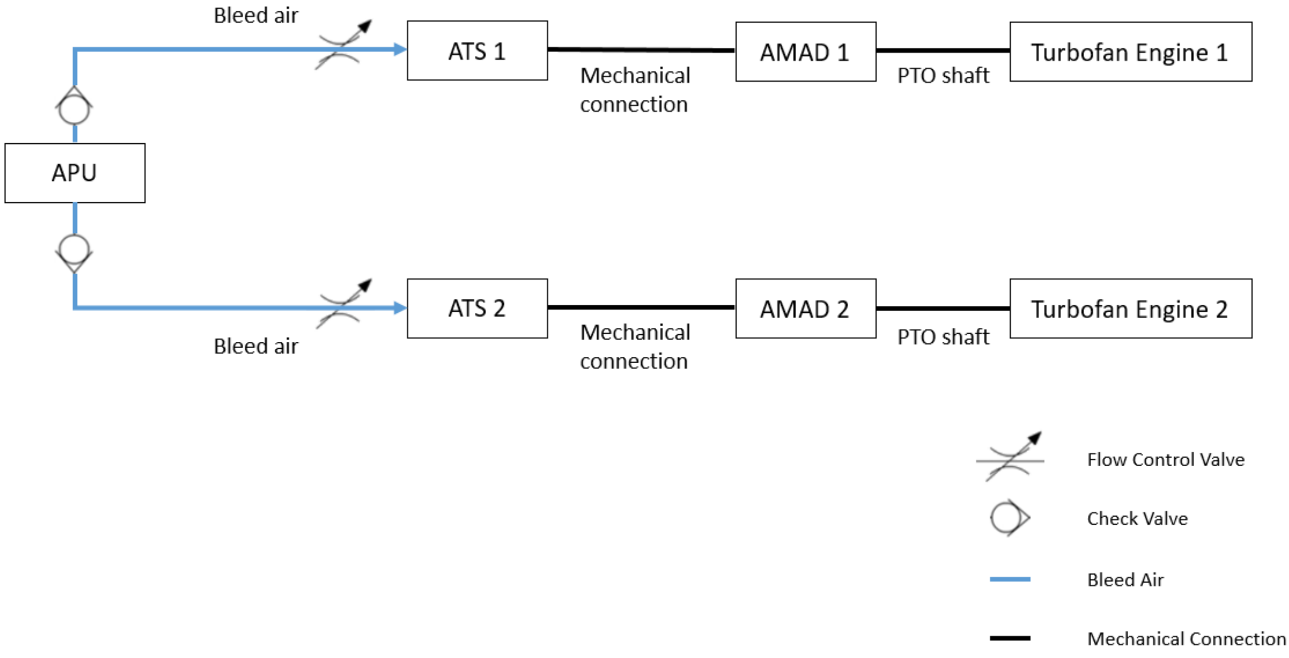

Figure 5: Air Turbine Starting System architecture

In this solution, APU is the main source of pressurized bleed air. When engine starting command is provided from cockpit for either engine 1 or engine 2, this bleed air is directed to ATS installed on the selected engine's AMAD. Flow control valve of the corresponding ATS is opened, and bleed air flow enters into ATS. ATS starts to rotate, and provides necessary torque to crank the engine. During this operation, accessories installed on AMAD (generally generator, pumps, etc.) also starts to rotate. When starter cutout speed is reached, ATS disengages and these accessories are driven by the engine. This process can be repeated for the other non-operating engine, or cross bleed start can be performed for the other non-operating engine's start. In cross bleed start, bleed air extracted from operating engine is directed to ATS of non-operating engine, and starting is implemented.

For the sake for simplicity, details of the system and other accessories are not shown on this architecture. Normally, there are bleed air extraction piping from engines, ECS bleed air piping, AMAD integrated air vehicle equipment, and other related pneumatic valves on ATSS system architecture. For ground support equipment assisted engine starts, additional piping and valves can also be included on this architecture.

Analysis Purpose and Requirement

Engine starting system performance analysis is important during air vehicle design process since appropriate starting system selection and system design must be achieved. In order to evaluate system performance, main engine starting requirements from customer, end-user or general aviation standards can be taken as a reference. According to the general aviation standards, unless there is a project specific requirement, 45 seconds may be targeted at sea level, standard day condition. It is also stated that 60 seconds may be targeted for hot and cold day conditions [Department of Defence, 2013].

Analysis Methodology

Engine starting system analysis is performed by analytical calculation methodology. Basic inputs required for this analysis are:

Air Vehicle manufacturer inputs: engine starting time requirement, mass moment of inertia of AMAD installed equipment, AMAD gear ratio (gear ratio between ATS output gear and PTO shaft), AMAD mechanical efficiency, pressure loss through APU and ATS piping.

Engine manufacturer inputs: engine drag-torque curve, mass moment of inertia of engine rotor, required starter torque curve.

ATSS manufacturer inputs: ATS torque curve, pressure and mass flow rate requirements of bleed air, pressure loss through pneumatic valves.

APU manufacturer inputs: APU performance results (bleed air mass flow rate and pressure).

Mathematical equations used for engine starting analysis are [Society of Automotive Engineers, 1962]:

$$T = I_m \alpha = I_m \frac{d\omega}{dt}$$

$$\omega = \frac{2\pi N}{60}$$

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

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

$$T_{idle} = I_m \frac{\pi}{30} \int_0^{N_{idle}} \frac{dN}{dt}$$

$$\Delta t = \frac{\pi I_m \Delta N}{30 T_{ave}}$$

Here;

T = net torque, Ib.ft

I_m = mass moment of inertia of the system, slug.ft^2

α = angular acceleration, rad/sec^2

ω = angular speed, rad/sec

t = time, sec

N = revolution per minutes, rpm

Δt = time increment between specified rpm interval, sec

ΔN = rpm increment, rpm

T_{ave} = average net torque in specified rpm interval, Ib.ft

ANALYSIS AND RESULTS

Analysis

Engine starting system analysis is performed for sea level, ground condition by using the in-house code that is generated in MATLAB. For in-flight engine restarts, windmilling, spooldown and starter assist conditions must be taken into the account and those conditions are out of scope for this paper.

For analysis, APU bleed air pressure and mass flow rate are obtained at predetermined engine starting conditions. Then ATS input air pressure and mass flow rate are estimated by considering pipe and valve losses in order to obtain relevant ATS torque. After foundation of ATS torque, engine starting time is calculated by using ATS torque, engine drag curves and mass moment of inertia of the system. The difference between ATS supplied torque and engine drag equals net torque, and this net torque provides angular acceleration of engine shaft. Since angular acceleration is the derivative of angular speed, time parameter can be obtained by integration between start initiation and idle speed.

Assumptions

1. AMAD mechanical efficiency is 95 percent.
2. Pressure loss through piping and pneumatic valves is 2 percent.
3. Gear ratio between ATS output shaft and PTO shaft is 1.
4. Engine oil type is MIL-L-23699.

Results

In this analysis, various atmospheric day conditions are studied at sea level. As a result of the analysis, standard day condition is found as the quickest engine starting condition, and starting time requirement is satisfied. Whereas, cold day is found the slowest as anticipated due to relatively higher engine drag torque, and starting time exceeds targeted requirement in the amount of 11.88 seconds.

Condition	Engine Starting Time
0 feet, standard day (T_{amb} = 15°C)	24.78 seconds
0 feet, hot day (T_{amb} = 49°C)	25.51 seconds
0 feet, cold day (T_{amb} = -33°C)	71.88 seconds

Table 1: Engine Starting Time Analysis Results

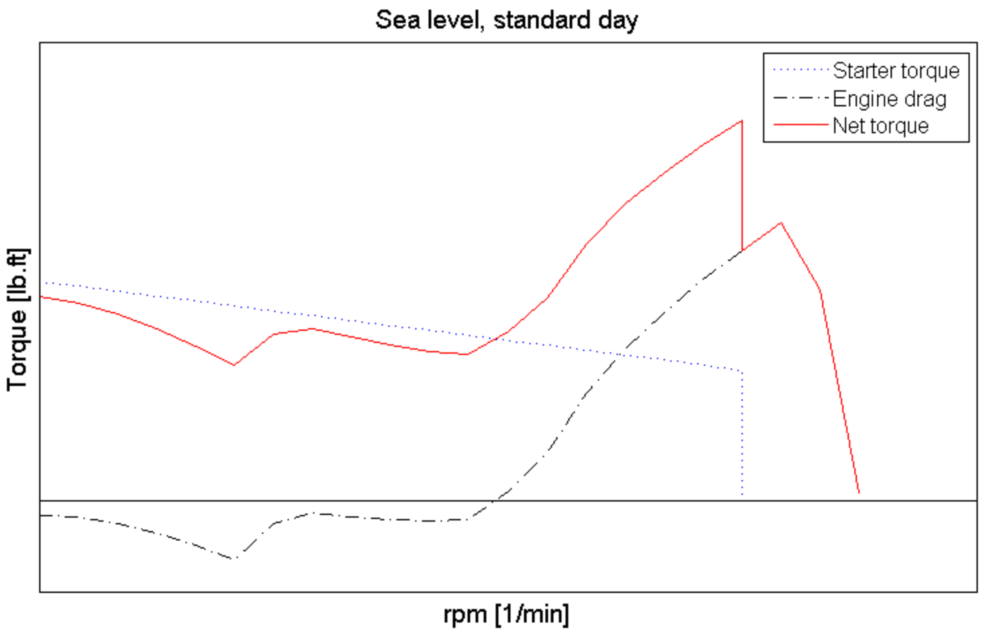

Figure 6: Sea Level, Standard Day Condition Torque Curve

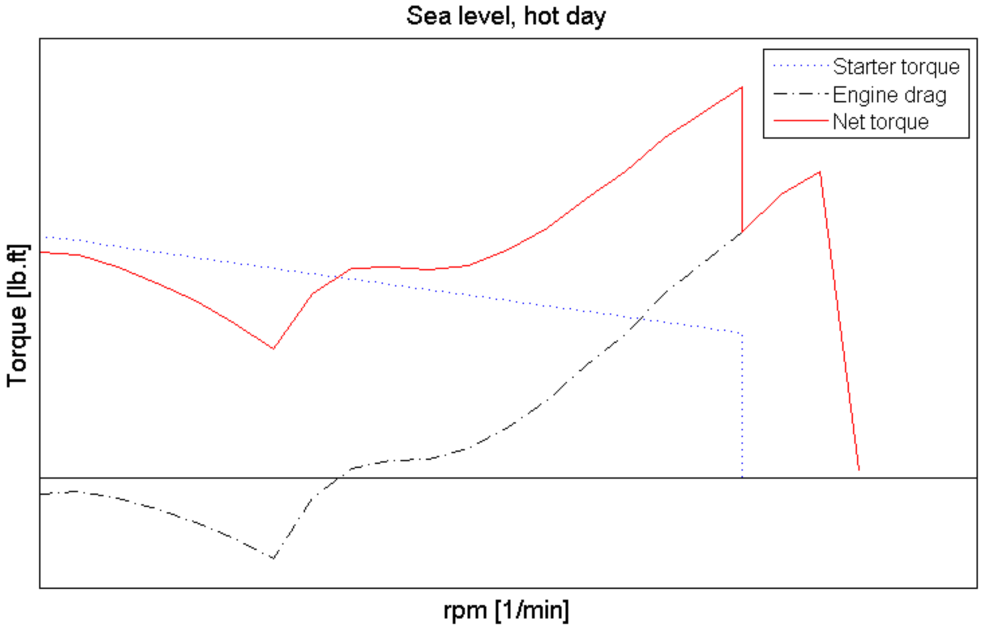

Figure 7: Sea Level, Hot Day Condition Torque Curve

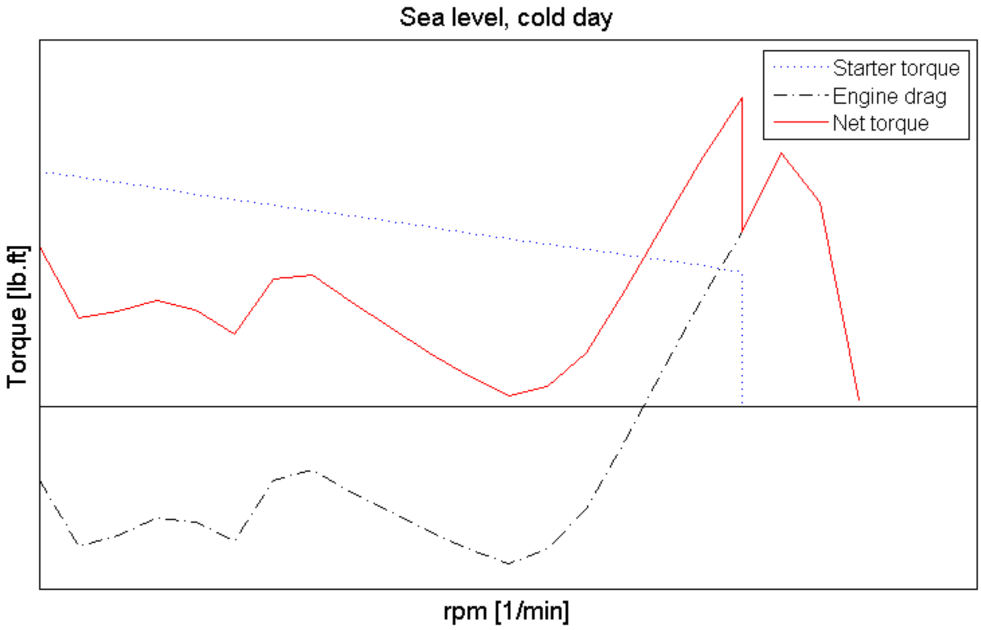

Figure 8: Sea Level, Cold Day Condition Torque Curve

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