Design of a Geared Turbofan Module for Small Unmanned Aircraft Applications

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This paper provides detailed analysis and considerations for the design, manufacturing, and testing of a fan module for a small, geared turbofan. The purpose of this research is to design a fan module to fill an operational gulf in small unmanned aircraft propulsion systems; to produce higher thrust and lower thrust specific fuel consumption than a turbojet, but also operate at higher air speeds and altitudes than a turboprop, while maintaining a higher propulsive efficiency. An optimized fan design that increases the range, endurance, and flight envelope for unmanned aircraft could significantly advance the applications of such aircraft in society. The fan module will be designed to integrate with a KingTech K45TP 5 kW turboshaft engine, of which its operating conditions will be used to size the fan. The design will start with a parametric cycle analysis to determine an optimal bypass ratio and fan compression ratio based on desired values and improvements of specific thrust and thrust specific fuel consumption. AEDsys software was utilized to verify the results of the parametric cycle analysis and later determined the geometry and sizing of two different fan designs; including airfoil shape, blade twist and length, number of blades, and overall fan diameter. The fan modules were modeled in SolidWorks and manufactured using a 3D carbon fiber printer. Last, the fan modules are tested on an 4 kW electric system in Oklahoma State University's wind tunnel and compared to the experimental results found in the design process. The results showed promise for the implementation of a ducted turbofan propulsive system for added range and endurance of unmanned aircraft.

I. Nomenclature

A	=	annulus area
$AEDsys$	=	aircraft engine design system
α	=	bypass ratio
α_1	=	inlet guide vane angle
C_p	=	constant specific heat
D	=	diffusion factor
η	=	polytropic efficiency
η_p	=	propulsive efficiency
γ	=	constant specific heat ratio
g_c	=	gravitational constant
i_{max}	=	mass flow rate

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IGV	=	inlet guide vane
m_{dot}	=	mass flow rate
M	=	mach number
MFP	=	mass flow parameter
ω	=	fan rotation rate
ψ	=	stage loading
PCA	=	parametric cycle analysis
P_T	=	parametric cycle analysis
π_f	=	parametric cycle analysis
R	=	gas constant
R	=	degree of reaction
r_h	=	hub radius
r_m	=	median radius
r_t	=	tip radius
σ	=	solidity
$SUAV$	=	small unmanned aircraft vehicle
τ	=	torque
S	=	specific thrust
T	=	thrust
T_T	=	total temperature
τ	=	torque
$TSFC$	=	thrust specific fuel consumption
u	=	axial velocity
U	=	product of omega and radius
$sUAS$	=	small unmanned aerial system
V	=	freestream velocity V_{peak}
peak voltage W_{fan}	=	fan shaft work/power

II. Introduction

The use of turbojet engines is attractive for high-speed applications to small, unmanned aircraft weighing less than 55 lbs. They provide a greater thrust to weight ratio than piston engines, but the high thrust specific fuel consumption (TSFC) limits the range and endurance of these vehicles. The thermal efficiency of the power plant is governed largely by compression ratio, which is small for centrifugal flow turbojets compared to their large axial flow counterparts. In addition, turbojets of this scale are limited geometrically by the size of their compressors. When the mission demands endurance and range, that same turbojet is generally modified into a turbo prop, which lowers the TSFC and increases thrust at the cost of a lower top speed. Given the increased demand on small unmanned aerial systems (sUAS) to produce higher propulsive efficiency, endurance, speeds, and longer range capabilities, an alternative between the turbojet and the turboprop is needed to fill the gap between them [Fig. 1].

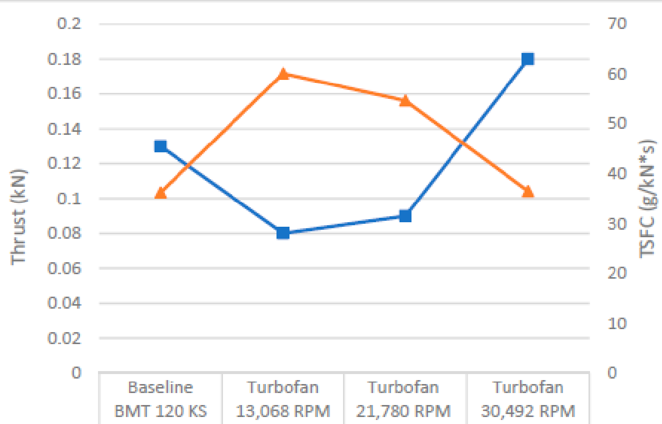
The desired approach is a turboshaft-driven fan module, which utilizes an external turbine to extract high energy flow from the turbojet. The candidate driver for the fan module used for sizing is the Kingtech K45TP. Constraints on this specific system include a fixed hub radius of 4 inches and a shaft power of 5.2 kW up to 9000 RPM, which will be addressed in the design process of the fan module. Utilizing the high energy density of hydrocarbon fuel, optimizing a fan module design for a turbojet will result in an increase in specific thrust (S), lower TSFC, and higher propulsive efficiency over the conventional turbojet. Conventional sUAS turbojets have an average TSFC of approximately 1.8(lbm/hr)/lbf and above, while turboprops in a similar configuration can achieve TSFC of 1.0(lbm/hr)lbf and below. Ngo showed that for a KingTech K45TP with both 2 blade and 3 blade propellor configurations a TSFC of around 0.5(lbm/hr)/lbf can be achieved at a throttle setting of 50% or higher [1]. This design and construction for small, unmanned aircraft application aims to increase range and endurance while maintaining high thrust output and increasing propulsive efficiency. The fan will be optimized for 5.2 kW of power at a rotor speed of 8000 RPM, for a flight speed of Mach 0.1. Design and efficacy of the fan module will be discussed though out this paper.

III. Background and Theory

A. Previous Work

Ngo et al. investigated this similar optimization problem, leading to several conceptual turbofan developments [1]. This particular study did not realize the design, but offers wind-tunnel data for a few turboprop configurations from which this paper will draw comparison. In relation, turboprops produce larger amounts of thrust than the proposed turbofan design, but are largely limited by airspeed. The application of turbofans to larger aircraft is well documented, since turbofans are in operation in many aircraft seen today. Due to their increased fuel efficiency, turbofan engines appear on nearly every airliner and are seen on many aircraft for military use. Despite a difference in size and application, the same performance improvements are particularly attractive for the increasing application of small, unmanned systems. sUAS often encounter mission limitations due to the flight range they are typically able to achieve. For turbojet SUAS that require high thrust, but need the added range to extend their mission capabilities, the turbofan design outlined in this paper seeks to satisfy both of those requirements. Well-designed fan modules could increase thrust produced by 50 percent, while decreasing TSFC by 50 percent. Success of this design, verified by wind-tunnel testing, broadens the applications of sUAS and potentially establishes a new propulsive platform around which future unmanned systems will be designed.

Large and Pesyridis investigated converting a BMT 120 KS 30lbf turbojet into a low-bypass turbofan for long-loiter applications [2]. They designed a fan and low-pressure compressor that augmented thrust from 30lbf to 40.5lbf and analyzed several performance parameters, one of the most important being TSFC. A summary of specific thrust and TSFC for their fan compared to the baseline turbojet is shown in Fig. 1. While they validated their design in the GasTurb program and utilized 3D CFD for the components, they did not fabricate any test hardware or attempt any experimental data acquisition. This study will attempt to not only design a fan stage for a 10 pound thrust core engine, but also focus on manufacturing and experimental testing to evaluate performance.



	Baseline BMT 120 KS	Turbofan 13,068 RPM	Turbofan 21,780 RPM	Turbofan 30,492 RPM
Thrust (kN)	0.13	0.08	0.09	0.18
Thrust Specific Fuel Consumption g/(kN*s)	36.242	60.088	54.6393	36.4814

Fig. 1 Comparison of the Baseline Turbojet Simulated Results to the Converted Turbofan.

Benini et al. examined the use of multiobjective evolutionary algorithms to design unmixed turbofan engines for UAV applications [3]. With the goal of replacing piston engines in UAVs, the turbofan engine designs require a minimization of flight time and thrust specific fuel consumption (TSFC). Due to the conflicting nature of the two goals, the authors developed a multiobjective evolutionary algorithm based on the non-dominated sorting genetic algorithm with inclusion of an elitarism mechanism to solve for optimized engine designs. The current study makes use of their design considerations, but in the context of simply adding a fan design to a current turboprop engine, the developed algorithms would not provide a valid solution. The current fan design study requires considerations of the provided turboprop engine performance and geometry.

At NASA, Grady et al. manufactured and tested gas turbine engine components made from non-metal polymer and ceramic matrix composite [4]. Their focus pertained to reducing emissions and noise for the GE CF34 high-bypass turbofan, but nonetheless, they achieved weight reductions and "the resultant propulsion system generated a 4.9% fuel burn improvement over the baseline" in the combustion liner, both the HPT and LPT. This was also achieved in the core nozzle, which eliminated the necessity for turbine cooling in the blades. Their findings show favorable potential for additive manufacturing (AM) use in this study's fan design. While AM is not a driving factor in this study, knowing this manufacturing technique is an option is valuable insight for future iterations. The blade geometry and sub assembly, once designed, could lead to complex shapes that could be best fabricated by AM.

B. Theory/Equations used for Design Process

1. Flight Condition

The flight conditions, which include the operational Mach number and altitude of operation, affect the inlet total properties of the engine. For this experiment, the wind-tunnel flow is set to standard day, sea-level standard day (SLS) pressure and temperature values. The parametric cycle analysis (PCA) is centered around the on-design condition for which the aircraft typically operates, so these considerations will be crucial for it's analysis. This design is set for a flight velocity of 100 knots at SLS conditions, but we do not expect to test at this speed; instead, testing will be conducted around 50 kts.

2. Preliminary Cycle Analysis

The calculations described in this paper are done as a 1-dimensional analysis, which considers thermodynamic properties across the mean radius of the fan blades, r_m, meaning this two-dimensional analysis does not include flow along the span of the fan blade. For establishing an estimated polytropic efficiency, a level of technology of 3 is selected for most major engine components. This determines the flow conditions entering the face of the fan, and helps define energy addition and pressure rise required of the design. A repeating row repeating stage with a constant mean radius was used for preliminary component design.

3. Sizing: MFP, Annulus Area, Hub and Tip Radii

The key to sizing the turbofan module is mass flow parameter (MFP), which is a function of Mach number and gamma. This allows the establishment of a relationship between Mach number, Constant specific heats ratio γ, and inlet size. The MFP for the turbofan module is calculated using *Equation 1*. [5]

$$MFP = M_{inlet}\sqrt{\frac{\gamma g_c}{R}}[1+\frac{(\gamma-1)}{2}{M_{inlet}}^2]^{\frac{(\gamma+1)}{2(\gamma-1)}} \tag{1}$$

MFP allows for the retrieval of annulus area by *Equation 2*, which is related to the MFP value previously calculated by mass flow rate and total air inlet properties. The annulus area is the total area in which air mass flow will be passing through to produce thrust.

$$A_{annular} = \frac{m_{dot}\sqrt{T_{ti}}}{P_{ti} cos\alpha MFP} \tag{2}$$

With the annulus area, a relationship between the hub and tip radii can be established.*Equation 3* displays this relationship. It is this step from which the inlet face sizing is finalized.

$$A_{annular} = \pi r_t^2 - \pi r_h^2 \tag{3}$$

The power required to operate the fan is critical. Assuming the optimal rpm at which the fan is spinning and the mass flow rate, the total power required by the fan is obtained using the Euler Pump Equation shown in *Equation 4*. The shaft power must meet these requirements. The actual power output of the KingTech K-45 TP is slightly above 5 kW. Knowing this, an optimal change in total temperature across the fan module can be found, and this will be a value to achieve with analysis in AEDsys.

$$\dot{W}_{fan} = \tau\omega = \dot{m}c_p(\Delta T_T) \tag{4}$$

4. Fan Component Design Choices

Designing an effective fan module for a geared turbofan engine is based on increasing the performance by in turn increasing the compression on the flow. To begin designing the fan module, some key factors are decided: solidity

σ, inlet flow angle α_1, shaft rotation speed ω and diffusion factor D. The variation of each of these values changes the performance of the fan module, and their values should be treated with utmost importance during the design and optimization phase.

1) *Solidity, σ*
   Solidity is the ratio of the blade chord to spacing. The higher this can be pushed, the greater command the blades can have on the incoming flow.
2) *Inlet Flow Angle, α*
   Inlet flow angle, α, is allowed to be 0 degrees, meaning the axial flow direction is unchanged when entering the fan. This value is specific for the on-design PCA performance at the flight condition around which the blade profiles are developed. In the instance of the addition of inlet guide vanes (IGVs), this value would increase and change the performance of the fan module. For this paper, IGVs will not be considered.
3) *Rotational Speed, ω*
   For this design, rotational speed ω is a design choice, but is also directly proportional to the power input. From previous experimental tests, as well as AEDsys iterations, ω is chosen to be $835\frac{rad}{s}$ [1]. For testing, this value will reflect the physical limitations of the experimental setup, and will also be a basis for analyzing the performance of the fan module in the wing tunnel.
4) *Diffusion Factor, D*
   Diffusion factor describes the amount of velocity lost across the fan blades in relation to the average velocity. It is desired to maximize this parameter to extract the most energy of the flow possible; an increased diffusion factor leads to an increased change in total temperature, which is in turn related to power and thrust. The limit of diffusion factor, as imposed by the total pressure loss coefficient, is shown to exist around 0.6. However, to maximize the fan pressure ratio, this design parameter will be increased past 0.6 to maximize performance.

5. Figures of Merit

These are parameters that articulate the performance of fan, compressor and turbine of an engine. The figures of merit considered for the design are: stage loading coefficient, flow coefficient, diffusion factor, total pressure loss, solidity, and degree of reaction.

1) *Stage Loading Coefficient, ψ*
   Stage Loading Coefficient is the ratio of stage work to rotor speed squared, as indicated in *equation 5*. Stage loading coefficient shows how much work is added to the flow by the compressor and fan or extracted by the turbine. Modern axial flow compressors have coefficients between 0.3-0.35 at the mean radius. A higher stage loading, although optimal for power output, can lead to the stall of the blades and considerable total pressure loss, especially in the case of pushing the diffusion factor above 0.6. [5]

$$\psi = \frac{g_c c_p (\Delta T_T)}{(\omega r_m)^2} \tag{5}$$

2) *Flow Coefficient, ϕ_f*
   Flow coefficient is the ratio of the axial velocity to the rotor speed. Modern flow coefficient values are between 0.45-0.55 at the mean radius. Note that for a fixed blade speed U, lower flow coefficients tend towards blade stall.

$$\phi_f = \frac{u}{\omega r_m} \tag{6}$$

3) *Degree of Reaction, R*
   Degree of Reaction is a ratio (Rotor static enthalpy rise / Stage static enthalpy rise) that is desired to be around 0.5 for a fan/compressor, so the rotor and stator rows will "share the burden" of increasing the enthalpy of the flow.

$$^\circ R = 1 - \frac{U}{2\omega r_m} \tag{7}$$

4) *Polytropic Efficiency, η*
   Polytropic Efficiency is the differential isentropic efficiency. Physically, polytropic efficiency is a ratio of the ideal work per unit mass to the actual work per unit mass for a differential pressure change. *Equation 8* shows

the mathematical method of calculating the polytropic efficiency. This is determined by the level of technology.

$$\eta = \frac{(\frac{P_{T_{1.3}}}{P_{T_1}})^{\frac{\gamma-1}{\gamma}} - 1}{\frac{T_{T_{1.3}}}{T_{T_1}}} \tag{8}$$

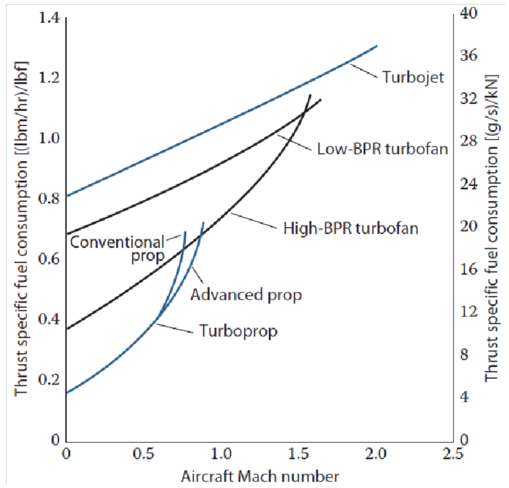


Fig. 2 Thrust Specific Fuel Consumption vs Mach Number for Various Propulsion Systems

IV. Methodology

Using theory developed from *Aircraft Engine Design, Third Edition*, preliminary calculations were performed with the desired flight conditions to size the turbofan profile. This step began with an on-design parametric cycle analysis from which compressor/fan blade figures of merit were determined, as well as the desired fan pressure ratio and bypass ratio. With the use of AEDsys and the KingTech K-45TP's power output of 5.2 kW, an optimized fan module was designed and analyzed. This AEDsys output was used to develop 3D models of all major fan components, which included; the hub, fan module, and the nacelle with all stator vanes. All parts were designed to be compatible with one another and ready to interface with the testing equipment . The fan blades and other components were first printed using a PLA 3D printer to test the fit to the desired testing set up, then finalized components were manufactured using carbon fiber 3D printers, outsourced to TechLab. The realized design was then exposed to in-flight conditions in the Propulsion Flexible-Use Wind Tunnel at Oklahoma State University. Data acquisition from the dynamometer reported the thrust produced using LabView, which was primarily used to track torque and thrust produced. Figures relating to engine performance, such as TSFC, will be determined mainly through the AEDsys program.

A. Design Process

A parametric cycle analysis (PCA) was performed to size the engine module. This process included the K45TP operational compressor ratio and combustion exit temperature, Tt4, as well as flight atmospheric conditions at 1000ft altitude. Initial values for fan and LPC compressor ratio were assumed initially, to output values for Specific Thrust, Thrust, and TSFC. The PCA was performed twice, first with the equations outlined in Theory, and second in the ONX subprogram of AEDsys. A level of technology (LOT) of 3 was assumed for all major components besides the combustor, which had an assumed LOT of 2 due to anticipated poor combustion at this scale. The resulting analysis gave efficiency values for all major components and pressure ratios for all subcomponents. Within ONX, carpet plots were created to choose bypass ratio α and desired fan pressure ratio π_f for the initial design, based on desired improvements in TSFC and specific thrust, S. A baseline was agreed upon before continuing past the PCA analysis; a $\pi_c = 2$, $\dot{m} = .29 lbm/s$ and $T_{t4} = 2000$. A bypass ratio of approximately 4 and a desired fan pressure ratio of 1.1 were chosen to advance the process. In *Figure 3*, the output results from ONX are shown.

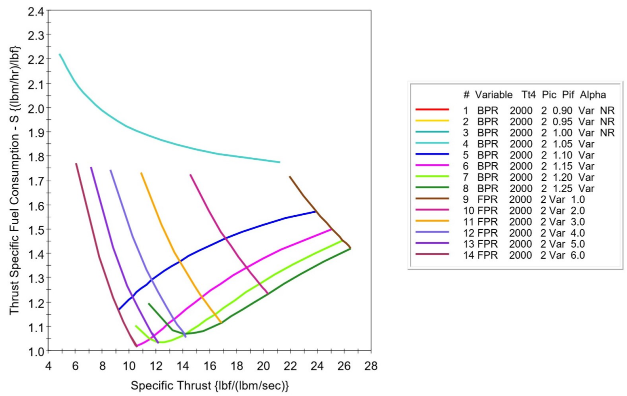


Fig. 3 Carpet Plot from AEDsys ONX

The design process in AEDsys's COMPR program was conducted by two separate teams. Each team's goal was to design a fan module that gave desirable compression ratios and increases in total temperature, to produce the most specific thrust while maintaining a low TSFC. Both teams approached the design task differently; one team favored variation in diffusion factor, and the other favored variation in fan blade solidity. Both designed fan modules will be manufactured and tested in the wind-tunnel at Oklahoma State, under the same testing conditions, to see which has better performance. The following sections detail each teams' specific design process.

B. Fan Design 1 - Favoring Diffusion Factor

Using the COMPR subprogram within AEDsys, manipulation of several different variables was conducted to achieve the desired fan pressure ratio. Diffusion factor was primarily increased to achieve desirable results, while most variables stayed the same: rotational speed, inlet mach number, air mass flow rate (based off of bypass ratio and initial candidate engine sizing), and polytropic efficiency. As established in *Design Choices*, ignoring the implementation of IGVs, M_i = 0.15, an inlet flow angle of α_i = 0 degrees, and a rotational speed of ω = 838 radians per second.

Several test cases were conducted, iterating through diffusion factor and solidity to change the fan pressure ratio and the hub radius of the blades, since the geometric constraints of the fan limited us between 2 and 4 inches for the fan hub. The resulting values for each analysis run were tracked and plotted in two different tables in Excel, and the resulting graphs were used to find the desirable diffusion and solidity values. It was decided to favor increasing diffusion factor over solidity to achieve the highest compression ratio. This process is shown in *Figure 4* below.

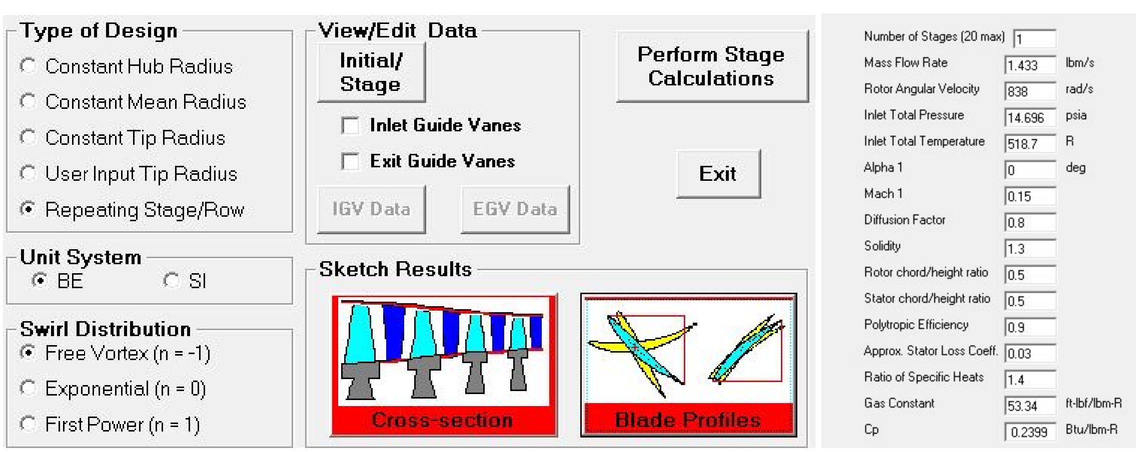


Fig. 4 AEDsys COMPR User Interface (Left) and Inputs Example (Right)

From this process, a diffusion factor of 0.8 and a solidity of 1.3 resulted in the highest achievable fan pressure ratio, 1.075, for the desired hub radius, 3.5 in. This fan pressure ratio was then confirmed in AEDsys subprogram ONX for

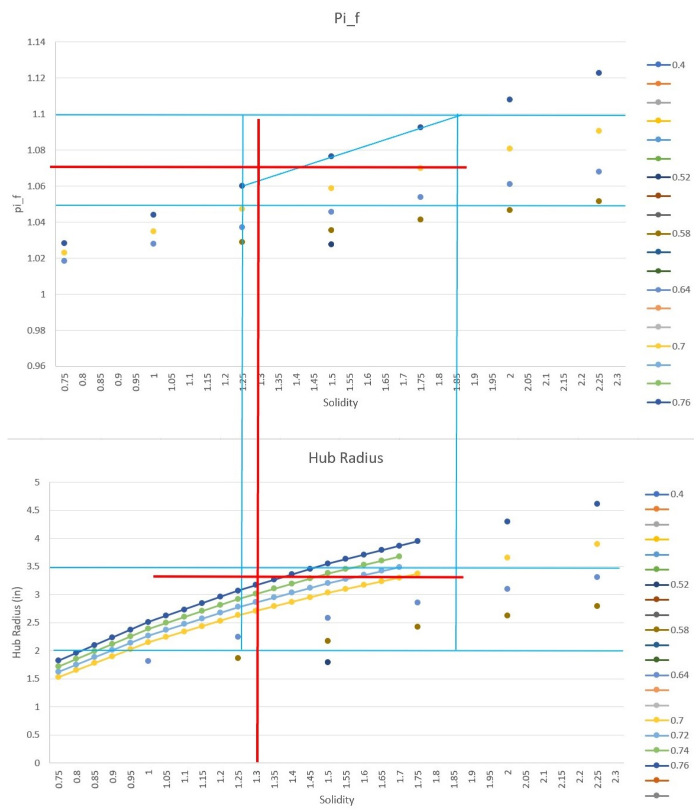


Fig. 5 Graphs Showing Variation in Hub Radius and Fan Pressure Ratio with Solidity (X Axis) and Diffusion Factor (Colored Lines)

our TSFC and Specific Thrust values. The results from this process are shown in *Figure 5-7* below. Specific Thrust was measured at 10.253 lbf/lbm/s, TSFC was measured at 1.469 lmb/hr/lbf, and the calculated thrust was 15 lbf.[6]

C. Fan Design 2 - Favoring Solidity

Using the COMPR program in AEDsys, the same variable manipulation was conducted by the second team, only this analysis focused on favoring an increase in fan solidity to output the desired values for change in total temperature and fan pressure ratio. Most variables were kept relatively the same compared to the first team's: an inlet mach of M_i = 0.15, an inlet flow angle of α_i = 0 degrees, and a rotational speed of $\omega = 835 rad/s$.
Several analyses were run, iterating on Diffusion Factor with emphasis on increasing Solidity, , to achieve the established π_f from the PCA. The resulting fan geometries began taking shape, and these iterations were performed until a fan with reasonable geometries was produced. The resulting design had a diffusion factor of 0.7, a higher Solidity of 1.65, and a π_f = 1.065. Returning to the PCA with the new pressure ratio, the TSFC, specific thrust, and thrust values of 1.305 (lbm/hr)/lbf, 11.587 lbf/(lbm/s), and 17 lbf, respectively. The final fan geometry produced a tip diameter of 8", a blade length of 0.76", and a blade chord length of 0.5".

D. Fan Design Comparison

In order to evaluate the parameters of the selected fan designs, they will be compared to one another as well as the Kingtech K45G1 turbojet engine. As discussed, the turboprop variation of this engine was selected for the initial design of the aforementioned fan systems. The base line turbojet has a max thrust of approximately 10 lbf and a TSFC of 2.08 (lbm/hr)/lbf. In order to show a significant improvement over the turbojet, the fan designs will need to provide a similar or higher thrust value at a much lower fuel consumption. Similar turboprop configurations can achieve a TSFC

```
Corr Flow = 001.43 lbm/s  Mass Flow = 001.43 lbm/s  Rotor Speed = 0838 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.3000
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 1  u2/u1 = 1.0000  Rotor c/h = 0.5000  Stator c/h = 0.5000
RESULT: Tt3/Tt1 = 1.0233  Pt3/Pt1 = 1.0753  DTt =012.09 R    AN^2=1.022E+09
  Hub   R = 0.4024  Dr = 0.7625  Ds = 0.8128  Phis = 0.0300  Eff = 0.8990
  Mean  R = 0.5000  Dr = 0.8000  Ds = 0.8000  Phir = 0.1203  r m = 03.859 in
  Tip   R = 0.5755  Dr = 0.7962  Ds = 0.7881  M1R  = 0.3028  U m = 0269.5 fps
  Flow  Area 1 = 0016.33  Area 2 = 0015.96  Area 3 = 0015.54 in^2
  Rotor  - # of Blades = 96  Chord = 0.333 in
  Stator - # of Blades = 98  Chord = 0.325 in
  Coefficients:  Stage Loading = 1.   Flow = 0.6199

   Station   1h    1m    1t    1Rm   2Rm   2h    2m    2t    3h    3m    3t
Prop:      ------------------------------------------------------------------
 Tt     R | 518.7 518.7 518.7 524.7 524.7 530.8 530.8 530.8 530.8 530.8 530.8
 T      R | 516.4 516.4 516.4 516.4 522.4 521.2 522.4 523.3 528.5 528.5 528.5
 Pt  psia | 14.70 14.70 14.70 15.30 15.21 15.83 15.83 15.83 15.80 15.80 15.80
 P   psia | 14.47 14.47 14.47 14.47 14.97 14.85 14.97 15.06 15.56 15.56 15.56
 M        | 0.150 0.150 0.150 0.285 0.149 0.303 0.283 0.267 0.148 0.148 0.148
 Vel ft/s | 167.1 167.1 167.1 317.1 167.1 338.7 317.1 299.3 167.1 167.1 167.1
 u   ft/s | 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1
 v   ft/s | 000.0 000.0 000.0 269.5 000.0 294.6 269.5 248.3 000.0 000.0 000.0
alpha deg | 00.00 00.00 00.00             60.44 58.20 56.07 00.00 00.00 00.00
beta  deg |                   58.20 00.00
radius in | 03.52 03.86 04.20 03.86 03.86 03.53 03.86 04.19 03.54 03.86 04.18
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Fig. 6 Fan Team 1 Results from COMPR Calculations

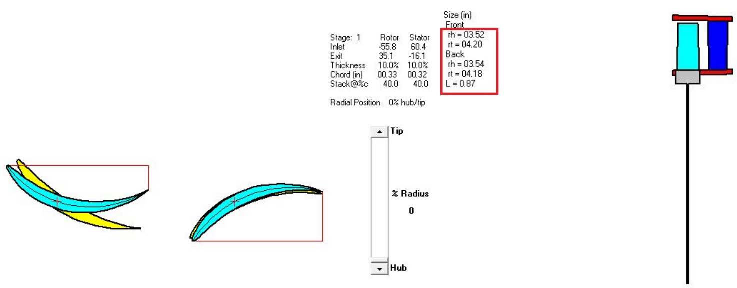

Fig. 7 Fan Team 1 Hub Sizing and Design Airfoil Geometries

of approximately 1.0 (lbm/hr)/lbf or lower. All AEDsys input parameters for both fan design 1 and 2 can are shown in Table 1 below. Initial calculations show that fan design 1 had the possibility of achieving a thrust of around 14lbf and a TSFC of 1.47(lbm/hr)/lbf. This equates to a 40% improvement in thrust with a 29% reduction in TSFC. Fan design 2 initial calculations show a possible thrust of 17lbf with a TSFC of 1.305 (lbm/hr)/lbf, these figures would give an 70% increase in thrust with a 37% reduction in TSFC. When comparing the initial results with the base line turbojet engine, the improvement in engine figures of merit looked promising to continue with manufacturing and testing of the proposed fan designs.

V. Testing Methodology (Wind Tunnel Setup and Data Acquisition)

Experimentation will be done in the Oklahoma State University flexible use wind tunnel facility (WTF) shown below in Fig. 12. The wind tunnel features a 16:1 contraction ratio with a 3 foot by 3 foot test section. It is capable of wind speeds up to 60 kts and features a traversing pitot probe with interactive data acquisition in Labview.

The device used to measure torque and thrust of the rotor during testing is the propeller dynamometer described by Lucido. The Futek MBA500 biaxial thrust-torque sensor and appropriate amplifier can be seen in Fig. 13. The sensor does require the use of two Futek FSH03863 amplifiers and NI DAQ card to acquire data. Data acquired is processed in LabView, which utilizes a calibration curve to obtain numerical values for both torque and thrust; this calibration curve is obtained identically to that described by Lucido. Angular speed will be measured and post-processed by the electronic speed controller described below via the CastleLink software package. This data is acquired via pulse counting thus the

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COMPR V6.00 - COMPRESSOR INITIAL DATA,  Design: 5,  Swirl: 1
Date - 4/7/2020    Time - 10:36:15 PM
Data File:Default Data
Corr Flow = 001.51 lbm/s  Mass Flow = 001.51 lbm/s  Rotor Speed = 0835 rad/s
Inlet Pt  = 014.70 psia   Inlet Tt  = 0518.7 R      Solidity    = 1.6500
Gamma = 1.4000 Gas Constant =53.34ft-lbf/lbm-R  Poly Eff = 0.900 Phis = 0.0300

COMPRESSOR STAGE: 1  u2/u1 = 1.0000  Rotor c/h = 0.6000  Stator c/h = 0.6000
RESULT: Tt3/Tt1 = 1.0204  Pt3/Pt1 = 1.0656  DTt =010.57 R    AN^2=1.072E+09
  Hub   R = 0.3795  Dr = 0.6450  Ds = 0.7223  Phis = 0.0300  Eff = 0.8991
  Mean  R = 0.5000  Dr = 0.7000  Ds = 0.7000  Phir = 0.1141  r m = 03.622 in
  Tip   R = 0.5885  Dr = 0.6997  Ds = 0.6797  M1R  = 0.2914  U m = 0252.0 fps
  Flow  Area 1 = 0017.21  Area 2 = 0016.87  Area 3 = 0016.47 in^2
  Rotor  - # of Blades = 85  Chord = 0.449 in
  Stator - # of Blades = 86  Chord = 0.440 in
  Coefficients:  Stage Loading = 1.   Flow = 0.663

   Station   1h    1m    1t    1Rm | 2Rm   2h    2m    2t    3h    3m    3t
Prop:      -----------------------------------------------------------------
  Tt      R | 518.7 518.7 518.7 524.0 524.0 529.3 529.3 529.3 529.3 529.3 529.3
  T       R | 516.4 516.4 516.4 516.4 521.7 520.4 521.7 522.6 526.9 526.9 526.9
  Pt   psia | 14.70 14.70 14.70 15.23 15.14 15.68 15.68 15.68 15.66 15.66 15.66
  P    psia | 14.47 14.47 14.47 14.47 14.91 14.78 14.91 15.00 15.42 15.42 15.42
  M         | 0.150 0.150 0.150 0.271 0.149 0.292 0.270 0.253 0.148 0.148 0.148
  Vel  ft/s | 167.1 167.1 167.1 302.4 167.1 326.7 302.4 283.2 167.1 167.1 167.1
  u    ft/s | 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1 167.1
  v    ft/s | 000.0 000.0 000.0 252.0 000.0 280.7 252.0 228.6 000.0 000.0 000.0
 alpha deg  | 00.00 00.00 00.00             59.24 56.46 53.84 00.00 00.00 00.00
 beta  deg  |                   56.46 00.00
 radius in  | 03.24 03.62 04.00 03.62 03.62 03.25 03.62 03.99 03.26 03.62 03.98
```

Fig. 8 Fan Team 2 Results from COMPR Calculations

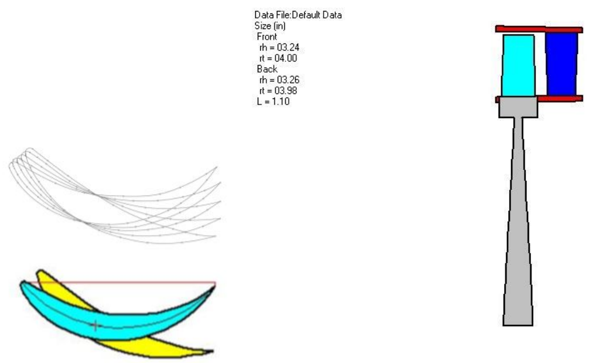

Fig. 9 Fan Team 2 Hub Sizing and Design Airfoil Geometries

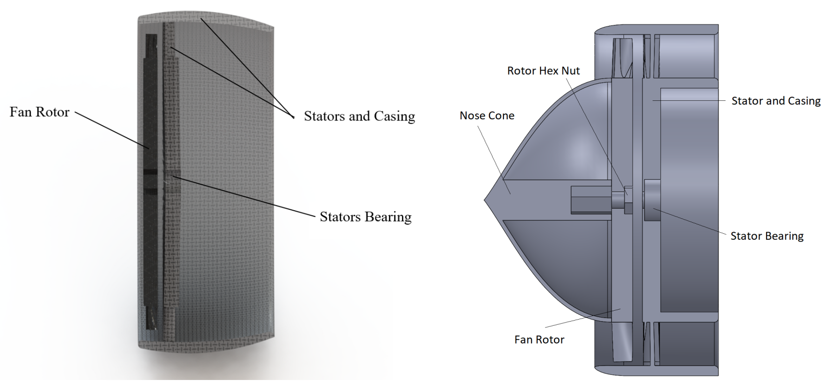

Fig. 10 Fan Module Cross Sections: Team 1 (Left) and Team 2 (Right)

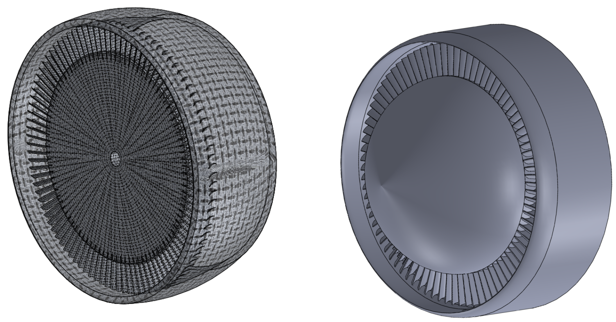

Fig. 11 Fan Module Isometric Views: Team 1 (Left) and Team 2 (Right)

Attribute	Fan Design 1 (High Diffusion)	Fan Design 2 (High Solidity)
Rotor Angular Speed, $\omega[rad/s]$	840	835
Inlet Mach, M_1	0.15	0.15
Bypass Ratio, α	4	4.2
Fan Pressure Ratio, π_f	1.075	1.065
Solidity, σ	1.3	1.65
Diffusion Factor, D	0.8	0.7
Thrust [lbf]	14	17
Specific Thrust, S [lbf/lbm/hr]	10.253	11.587
TSFC [lbm/hr/lbf]	1.469	1.305
Rotor Blades	96	85
Stator Blades	98	86
Hub Radius, r_h $[in]$	3.52	3.24
Blade Tip Radius, r_t $[in]$	4.2	4.0
Flow Coefficient, ϕ_f	0.6199	0.663
Stage Loading, ψ	1	1
Polytropic Efficiency, η	0.9	0.9
Degree of Reaction, R	0.5	0.5

Table 1 Comparison of Fan Designs

only information required is the number of poles inside the motor.

The setup will be identical to that of Lucido, with the except of the motor used to turn the rotor is the Great Planes Rimfire 50cc, which has a KV rating of 230 RPM/V and a peak continuous power of 5kW. Controlling this motor is the Castle Creations Phoenix Edge 170HV electronic speed controller (ESC). This speed controller is compatible with DC sources rated between 22-50V, and can supply a peak current of 170A. The power source is the Magna-Power Electronics SL32-125/480+LXI DC Power supply, which can supply up to 125A at 32V continuous voltage. Table 2 below shows the values which are attainable with the current configuration compared to the estimated values which are required to evaluate the fan at the design point. Equations 9 and 10 are referenced in the performed calculation.

$$\omega_{max} = V_{peak} * KV \tag{9}$$

$$i_{max} = \frac{W_{peak}}{V_{peak}} \tag{10}$$

As shown, the current power system configuration will not be able to reach to the design point for testing and

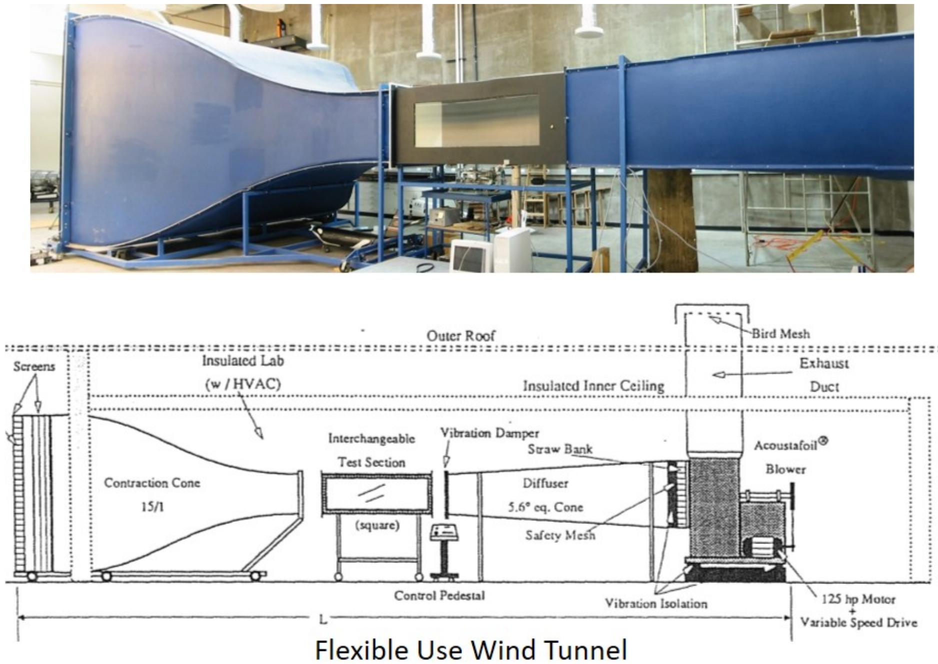

Fig. 12 Propulsion Flexible-Use Wind Tunnel at Oklahoma State University

Fig. 13 Futek Biaxial Thrust-Torque Sensor (Left) and Amplifier (Right)

evaluation; the RPM can be met but the current supply is not sufficient. To address this issue, a 12S lithium polymer (LiPo) battery will be used in place of the Magna Power DC Power supply in conjunction with a GT Power inline power meter to capture voltage and current. The battery discharge rating is 60C, or 60 times the capacity in Amp-hours. For example, a 60C battery with 5000 Ah of capacity can discharge at 300 Amps. This column is shown in Table 2 to illustrate the need for a battery for testing at the design point.

A. Experimental Procedure

The procedure for acquiring data will follow the test matrix shown in Table 3. The data collected from the experiment will be compared against analytical studies performed using AEDsys. Results obtained will include measured thrust and torque vs. analytical thrust and torque. Thrust and torque can be obtained analytically with inlet and exit pressures, velocity, motor power, and exit angle at station two in conjunction with the equations given in Section III. The test points are as follow:

Value	Magna Power DC Power Supply (max)	Required (est.)	12S 5000mAh LiPo Battery (max)
$\omega_{peak}(rpm)$	7360	6500	11500
$i_{peak}(A)$	125	141.5	300

Table 2 Estimated and peak power system performance

Test Point	Angular Speed (rpm)	Freestream Speed (knots)
1.1	3500	0 (static)
1.2	5000	0 (static)
1.3	6500	0 (static)
2.1	3500	50
2.2	5000	50
2.3	6500	50
3.1	3500	65
3.2	5000	65
3.3	6500	65

Table 3 Test matrix for Fan Design Varying Rotor Angular Speed and Flight Speed

VI. Results

VII. Conclusions and Discussion

VIII. Future Work

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References

[1] Ngo, A., Rhyne, C., KC, R., Rouser, K., and Salinas, D., "Investigation of a Geared Turbofan for Small Unmanned Aircraft Systems," *AIAA SciTech 2019 Forum*, 7-11 January 2019.

[2] Large, J., and Pesyridis, A., "Investigation of Micro Gas Turbine Systems for High Speed Long Loiter Tactical Unmanned Air Systems," *MDPI*, 2019.

[3] Benini, E., and Chiereghin, N., "Turbofan multiobjective-multipoint optimization for UAV/UCAV application," *Aircraft Engineering and Aerospace Technology*, 2013.

[4] Grady, J., Halbig, M., and Singh, M., "A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing," *International Society for Airbreathing Engines*, 2015.

[5] Mattingly, J. D., and Boyer, K. M., *Elements of Propulsion: Gas Turbines and Rockets*, 2nd ed., chapter and pages.

[6] Mattingly, J. D., Heiser, W. H., Boyer, K. M., Haven, B. A., and Pratt, D. T., *Aircraft Engine Design*, 3rd ed., chapter and pages.