Effect of Variable Inlet Guide Vanes (VIGV) on a Small Gas Turbine Engine

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Variable inlet guide vanes are used throughout the gas turbine industry to improve compressor performance and increase the compressor off-design efficiency. In recent years, expendable unmanned aircraft systems (UAS), powered by small gas turbines, have become popular. Because the UAS are expendable, any improvement in their fuel efficiency, and thus their endurance, will provide a large increase in value to the end user. This paper outlines the design of a prototype variable inlet guide vane system for use on a small gas turbine engine. A flight ready system was then additively manufactured and tested on a JetCat P100-RX gas turbine engine. This paper analyzes the results from the test, discusses the effect of different vane angles on the engine, and performs a use case analysis to determine the viability of the proposed variable inlet guide vane system.

I. Nomenclature

C	=	Blade Absolute Velocity
ECU	=	Electronic Control Unit
EGT	=	Exhaust Gas Temperature
GSU	=	Ground Support Unit
$\dot{m}_{fuel}$	=	Fuel Flow
$NACA$	=	National Advisory Committee for Aeronautics
NI	=	National Instruments
PLA	=	Polylactic acid
SLA	=	Stereolithography
$TSFC$	=	Thrust Specific Fuel Consumption
U	=	Blade Local Tangential Speed
UAS	=	Unmanned Aircraft System
$VIGV$	=	Variable Inlet Guide Vane
W	=	Blade Relative Velocity
$_x$	=	Axial
$_1$	=	Rotor Entrance Station
$_2$	=	Rotor Exit Station
$_\theta$	=	Angular

II. Introduction

Variable guide vanes have been used for the past 70 years on large scale commercial and military jet engines. They are commanded by the engine control system to change their angle in order to better match the engine to its operating condition. Variable guide vanes allow the compressor to operate more efficiently, and at a higher stall margin, thus improving engine fuel efficiency, lowering exhaust emissions, and increasing the engine reliability [1]. Recently, small gas turbine engines have become an area of interest because of their potential use in Unmanned Aircraft Systems (UAS) [2]. Additionally, small gas turbine engines allow researchers to perform tests and experiments on gas turbine engines without the need for expensive test infrastructure. The modern hydraulic actuator design of variable guide vane systems

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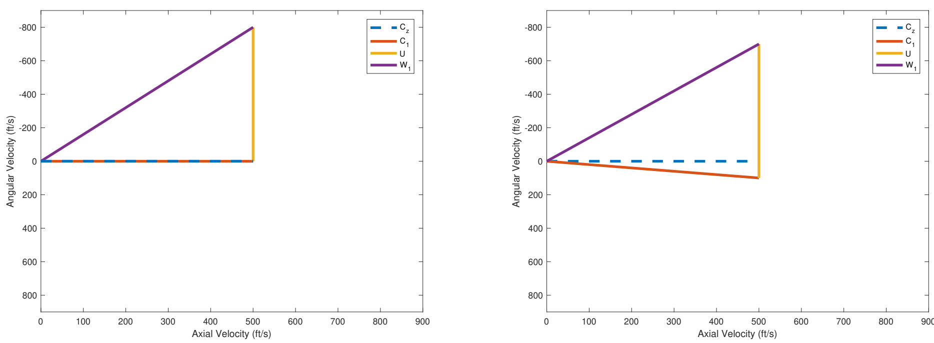
is not suitable for small gas turbine engines due to its high weight, complexity and size. This paper investigates a new, rapidly prototyped, Variable Inlet Guide Vane (VIGV) system installed on a 20 lbf thrust, JetCat P100-RX engine. Different VIGV angles were tested at a variety of engine shaft speeds to determine the effect on the engine at different operating conditions. The experimental set-up included instrumentation to measure the engine thrust along with other key metrics. This information was used to measure the overall engine performance and draw key conclusions.

III. VIGV Design

The function of VIGVs is to adjust the pre-whirl of the incoming flow to the compressor. Whirl is the component of the absolute velocity that is parallel to the impeller tangential velocity. It is defined as positive in the direction of impeller rotation. Equ. 1 shows the Euler Turbomachinery equation.

$$\Delta(h)_{1,2} = \Delta(UC_\theta)_{1,2} \tag{1}$$

The equation shows that when the pre-whirl angle is positive, the work done by the stage decreases. Fig. 1 illustrates the effect on the entrance velocity triangle.



(a) Entrance velocity triangle with 0° pre-whirl **(b) Entrance velocity triangle with 10° pre-whirl**

Fig. 1 Effect of pre-whirl on the entrance velocity triangle

Although the pre-whirl reduces the work done by the compressor stage, a positive pre-whirl can increase the efficiency of the stage by lowering the relative rotor entrance Mach Number [3]. Fig. 2 demonstrates the effect on the compressor efficiency as a function of compressor pressure ratio and pre-whirl angle.

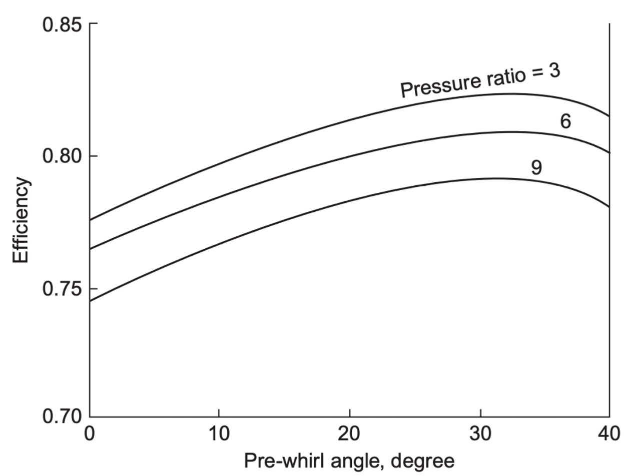


Fig. 2 Centrifugal compressor efficiency as a function of pressure ratio and pre-whirl angle [3]

Modern jet engines actuate their variable guide vanes with heavy hydraulic systems that utilize linear motion, bell cranks, and unison rings to move all the guide vanes [4]. These systems are heavy and expensive, but practical for multistage systems since a single actuator can move multiple stages of guide vanes. An example variable guide vane system for a large jet engine is shown in Fig. 3.

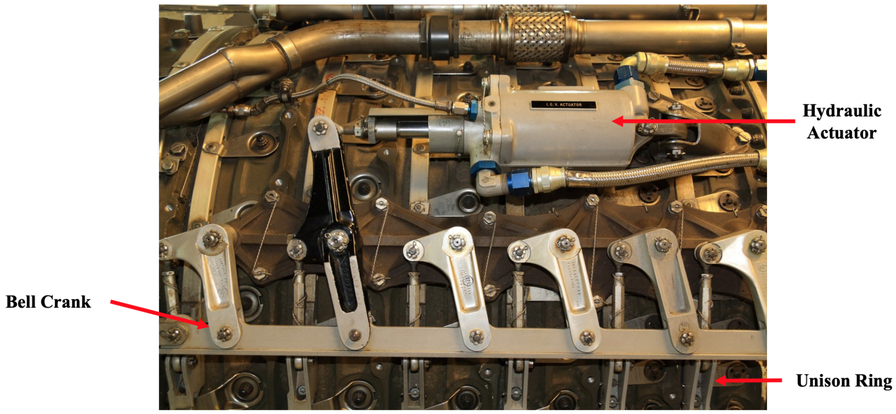


Fig. 3 Modern variable guide vane actuation system [5]

The JetCat P100-RX flow path is a single stage centrifugal compressor, a burner, a single stage axial turbine, and a convergent nozzle [6]. Fig. 4 shows an isometric view of the engine.

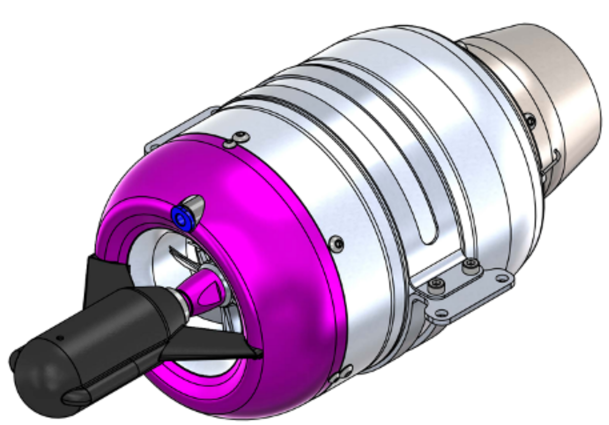


Fig. 4 JetCat P100-RX isometric view [6]

On single stage compression systems, like the JetCat P100-RX, implementing a modern variable guide vane actuation system is not optimal. The manufacturing complexity and high cost outweigh the potential performance benefits. Additionally, the weight of the hydraulic actuator, fluid, and pump are much heavier, relative to an electric actuator, at this scale. Therefore, alternative actuation methods must be investigated.

There are three different options to actuate the VIGVs: a geared mechanism, a pneumatic mechanism, and a linear actuator mechanism [7]. A Pugh matrix is created to evaluate these mechanisms based on the following criteria: weight, manufacturing simplicity, vane angle precision, and cost. The simple implementation in small gas turbine engines and the ability to rapidly prototype the design were emphasized during the evaluation of the mechanisms. Emphasizing these features increases the chances of the design being implemented. Table 1 shows the completed Pugh matrix.

Table 1 Pugh matrix evaluating VIGV architectures

Mechanism	Weight	Manufacturing Simplicity	Precision	Cost	Total
Geared	2	1	2	1	**6**
Pneumatic	3	3	2	3	11
Linear actuator	1	2	1	2	**6**

The Pugh matrix study shows a tie between the geared mechanism and the linear actuator mechanism. Therefore, both systems were designed, assembled, and evaluated. The geared mechanism is designed first, due to its lower relative cost. The geared mechanism works by using an outer drive gear to rotate the individual IGV gears. This system would only require one motor for actuation. An example 3D computer model of the geared mechanism is shown in Fig. 5.

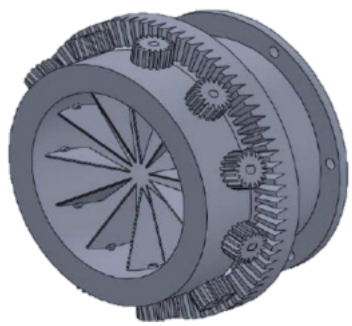


Fig. 5 Geared VIGV concept [7]

First, the outer casing that houses the VIGVs was designed in SOLIDWORKS [8]. The VIGV system will be installed before the centrifugal compressor, surrounding the starter motor. Therefore, the outer casing must safely secure itself onto the front of the engine and cannot interfere with the starter motor. This was done by creating a part that merges the inlet cowl and VIGV outer casing. The new part replaces the pink inlet cowl seen in Fig. 4. This part was 3D printed using polylactic acid (PLA) filament and fit tested to the engine. Small adjustments to the design were made until a proper fit was achieved. This part is interchangeable between the geared mechanism and the linear actuator mechanism. The completed outer casing is shown in Fig. 6.

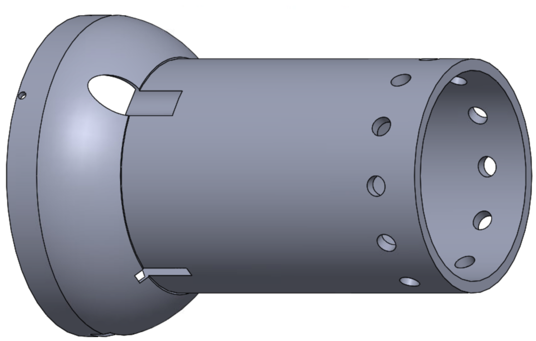
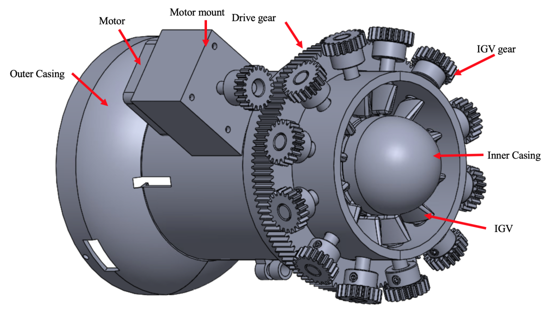
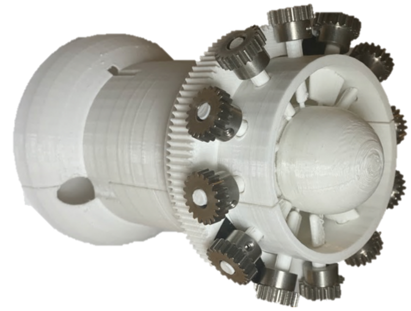


Fig. 6 Inlet cowl and outer casing integrated part

The remaining parts for the geared mechanism were designed in SOLIDWORKS and added to the assembly, including the inner casing, the main drive gear, the inlet guide vanes, and the motor mount. All these parts were 3D printed out of PLA filament and iterated multiple times due to interference, manufacturing, and assembly issues. The individual inlet guide vane gears and the motor were purchased externally. A labeled 3D model of the final geared VIGV assembly is shown below in Fig. 7a. A prototype of the geared VIGV system, without the motor mount, is shown in Fig. 7b.



(a) Labeled geared VIGV assembly

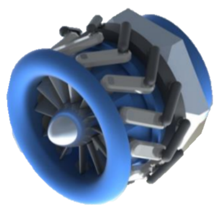


(b) Manufactured geared VIGV assembly

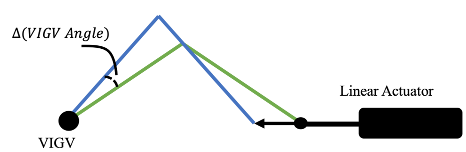
Fig. 7 Geared VIGV design

Testing the geared prototype revealed that the individual guide vane gears had the tendency to slip. This caused misaligned vanes and if the issue was left unfixed, it would lead to inlet blockage and distortion. This would in turn lead to rotating stall, which is unacceptable. This issue could potentially be resolved with better gear design and tighter tolerances, however, due to limited resources, this path was not pursued and the geared actuation method was eliminated. This design could be revisited in future work.

With the geared design eliminated, the linear actuator VIGV design was pursued. The linear actuator system works by moving a unison ring forward and back with a pair of linear actuators. A series of levers are connected together with one end connected to a unison ring and the other to a vane. An example 3D computer model of a linear actuator mechanism is shown in Fig. 8a. The crank slider mechanism is adapted from Rusovici et al and shown in Fig. 8b [9].



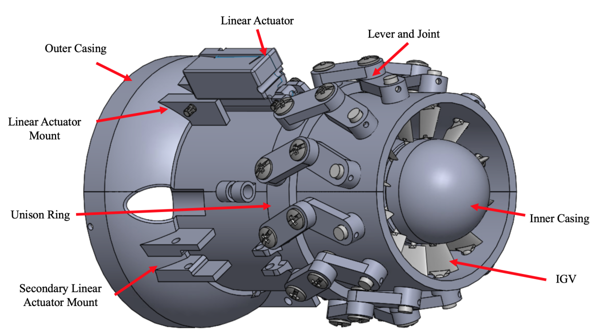
(a) Linear actuator VIGV architecture [9]



(b) Crank slider mechanism

Fig. 8 Linear actuator VIGV concept

The linear actuator system shares some of the same parts as the geared system, including the inner and outer casing. Both the unison ring and the levers were designed from scratch and printed from PLA. Binding barrels were purchased externally and acted as joints between the unison ring and the levers. The linear actuators and an Arduino microcontroller were also purchased externally. A labeled 3D model of the linear actuator VIGV assembly is shown below in Fig. 9a. The manufactured linear actuator VIGV assembly is shown in Fig. 9b.



(a) Labeled linear actuator VIGV assembly

(b) Manufactured linear actuator VIGV assembly

Fig. 9 Linear actuator VIGV design

Testing showed that the linear actuator system performed better than the geared system when considering vane precision and control. The weight of the linear actuator system is 20% lower, or 0.15 pounds lighter, than the geared system, even with two linear actuators. The cost of the linear actuator system is higher than the geared system by $50 because of the extra actuator. Since vane precision and control is a priority, the down selected architecture is the linear actuator VIGV system.

Prior to testing, the outer casing and the guide vanes were specially manufactured. Due to its proximity to the combustor, the pink nacelle experiences high temperatures. Since the outer casing replaces the nacelle, the outer casing was printed out of ULTEM 1010, a high temperature thermoplastic. Additionally, the inlet guide vanes were redesigned to follow a NACA 63-(10A4K6)06 profile as recommended by Aungier [10]. The guide vanes were printed using Stereolithography (SLA) printing to get an accurate blade profile that wouldn't be achievable using traditional fused filament fabrication. These manufacturing methods increase the cost of the system, but are 40% cheaper than the metal CNC alternative at a large scale [11].

Overall, the modern design of VIGV systems makes it difficult for manufacturers to include them on their small gas turbine engines. The proposed VIGV system has high precision, can be rapidly manufactured and installed onto the engine, and costs $276 per unit. The proposed design lowers the barrier to entry for manufacturers to include VIGV systems onto their engines.

IV. Experimental Methodology

To analyze the effects from adding VIGVs to the JetCat P100-RX engine, a series of tests must be done. During these tests, engine data is collected by sensors. The engine ground support unit (GSU) provides exhaust gas temperature, shaft speed, pump voltage, and throttle data. The engine is also mounted in a test stand with a load cell to measure thrust. The load cell sends signals to a National Instruments (NI) data acquisition module. A NI chassis provides power to the module and sends the sensor signals to the PC. A LabView script was created that interprets the sensor signals into meaningful data. In post-processing, the data are filtered and visualized in MATLAB to fully understand the engine performance. To control the VIGV angles, commands are sent via the Arduino integrated development environment to an Arduino microcontroller that commands the actuators to move the guide vanes. Fig. 10 illustrates the data collection and engine control schematic for the tests.

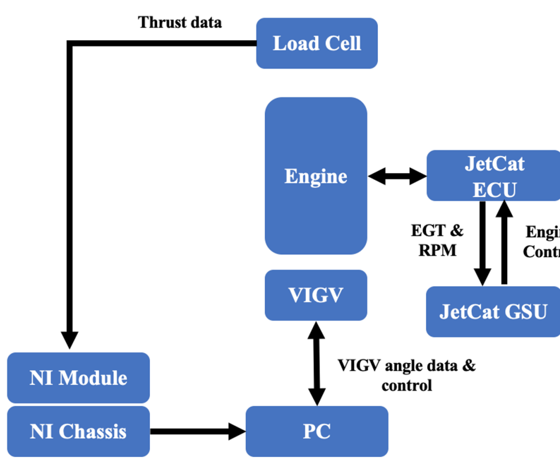


Fig. 10 Block diagram of data collection and engine control

Before testing, the VIGV system is actuated multiple times to measure its reliability. This is done to ensure that the mechanism does not malfunction during testing, cause distortion, or cause a blockage. The first test collects baseline data of the engine without the VIGV system installed. In the second test, throttle and vane angles are changed systematically to capture the effect across many operating conditions. During all tests, the EGT and the RPM are monitored to ensure that these values do not exceed the specified manufacturer limits. Furthermore, after changing the vane angle or throttle position, the engine was left to stabilize for at least 10 seconds in order to get a more accurate steady state thrust measurement. Table 2 summarizes the test plan.

Table 2 **VIGV test plan summary**

Test Number	Vane Angle (°)	Throttle position (%)
1	No VIGV system installed	60, 70, 80, 90, 100, 90, 80, 60
2	0, 15, 25, 35	60, 70, 80, 90, 100

The goal of the tests is to collect enough data in order to evaluate the effect of different vane angles on the engine.

V. Results and Discussion

The testing was conducted at the Georgia Institute of Technology Ben T. Zinn Combustion Laboratory. The experimental set up is shown in Fig. 11.

(a) Test stand and instrumentation set-up

(b) VIGV system installed on the engine

Fig. 11 Experimental set-up

Atmospheric conditions were noted at the start of each test in order to correct the measured thrust using Equ. 2.

$$F_{corr} = \frac{F}{\delta} \tag{2}$$

The first test acted as a baseline and collected data for the unmodified engine. The load cell data were reduced to remove noise and then plotted against time. Results are shown in Fig. 12.

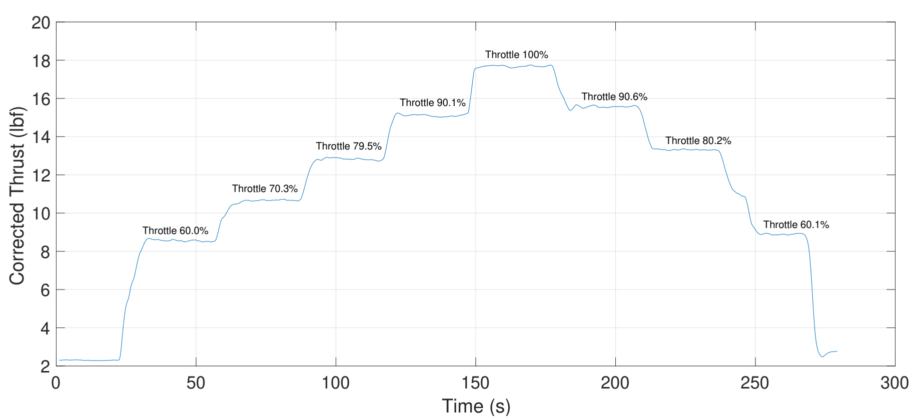


Fig. 12 Baseline corrected thrust as a function of time and throttle percentage

Precise throttle control is difficult to achieve with the current experimental set up. It would be impractical to try and match the same throttle settings in the VIGV test as the baseline test. Also, results show that a 1% change in throttle setting can lead to a 2.5% change in measured thrust. Therefore, it is imperative to create a relationship between throttle setting and thrust. The average thrust values were plotted against their respective shaft speed and a linear regression was fit. This is shown in Fig. 13.

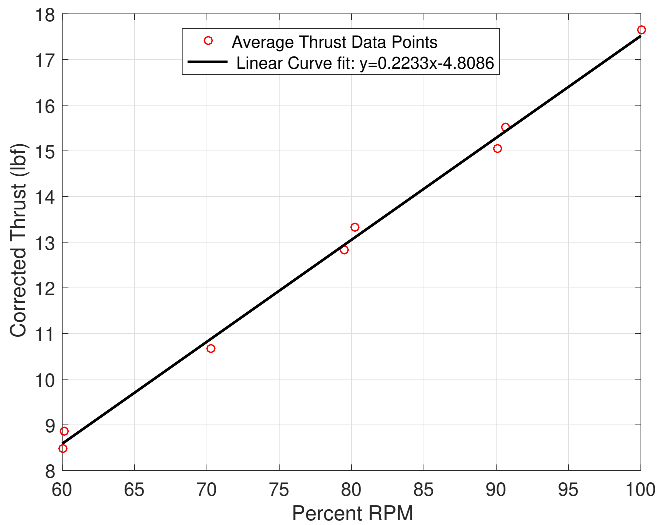


Fig. 13 Measured thrust as a function of shaft speed

In the second test, the pink nacelle was removed and the VIGV system was installed in its place. At each throttle condition, four vane angle settings were tested: 0°, 15°, 25°, and 35°. As above, the load cell data were reduced to remove noise and then plotted against time. Additionally, using the linear regression equation from Fig. 13, the baseline expected thrust was overlaid so a true comparison can be seen between the baseline engine performance and the engine performance with the VIGVs. Results are shown in Fig. 14.

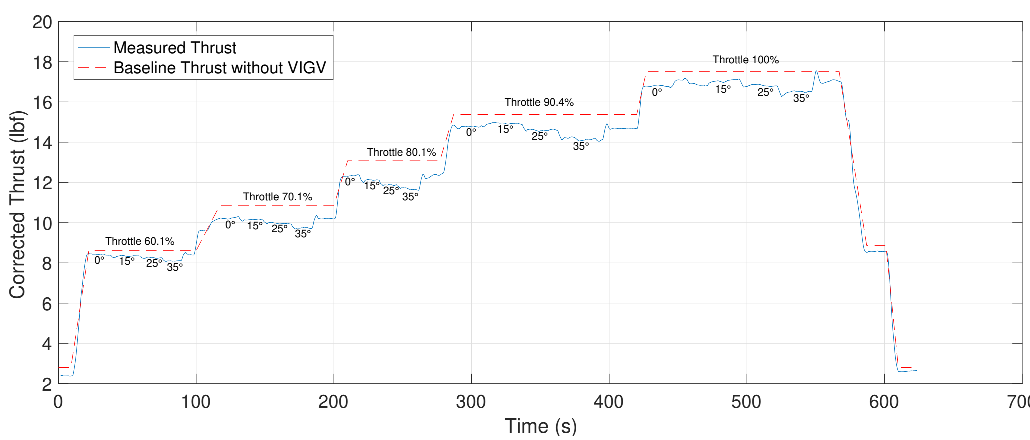


Fig. 14 Corrected thrust as a function of time, vane angle and throttle percentage

It is evident from the figure that the thrust decreases when the VIGV system is installed. The average decrease in thrust across all throttle conditions, at 0° vane deflection, is 4.5%. The decrease in thrust can be attributed to an unoptimized inner and outer casing design. These parts act as the new inlet for the engine and require careful redesign. Lip design, capture area, and smoothing of the casings should all be considered in future work.

Fig 14 is also useful in showing that changing the VIGV angle does in fact affect engine performance. For 60.1%, 70.1%, and 80.1% throttle conditions, increasing the VIGV angle only makes performance worse. This behavior is not entirely unexpected. At low throttle conditions, the compressor is not spinning as fast and thus, the rotor relative entrance Mach Number is not high. At these conditions, the data shows that it is not worth sacrificing stage work to lower the rotor relative entrance Mach Number. The losses are not high enough for it to be worth it in terms of improving engine performance. In future studies, negative pre-whirl should be explored for these low throttle conditions. At 90.4% and 100% throttle conditions, the engine performance improves at 15° vane angle, and then performance decreases as vane angle increases further. This suggests that, at these throttle conditions, there is an optimal point of positive pre-whirl that maximizes the engine performance. Table 3 summarizes the average thrust values for each vane angle and each throttle condition.

Table 3 Average thrust as function of vane angle and throttle

	Average Thrust (lbf)				
Throttle Setting	Baseline without VIGV	Vane Angle 0°	Vane Angle 15°	Vane Angle 25°	Vane Angle 35°
60.1%	8.61	8.42	8.32	8.23	8.10
70.1%	10.84	10.18	10.16	9.94	9.73
80.1%	13.08	12.32	12.10	11.87	11.65
90.4%	15.38	14.77	**14.96**	14.64	14.13
100%	17.52	16.72	**17.11**	16.80	16.53

At 90.4% throttle, a 15° vane angle improves the thrust by 1.2% from the 0° case. At 100% throttle, a 15° vane angle improves the thrust by 2.3% from the 0° case. It should be noted that the measured EGT and fuel pump voltage in both cases increased as well. This would suggest an increase in fuel flow. Unfortunately, the manufacturer specifications only provide a fuel flow as a function of percent throttle. Therefore, with the current relationship, at a constant percent throttle, a higher thrust would indicate a lower thrust specific fuel consumption (TSFC), even if EGT or pump voltage is higher. Further testing would be needed to relate pump voltage to fuel flow.

The experiments above are conducted at a constant throttle. Realistically, a constant thrust is required during flight. Using the linear regression equation from Fig. 13, the new required throttle setting can be found. Then, the fuel flow, and thus the TSFC, can be calculated using Equ. 3.

$$\dot{m}_{fuel} = (0.1487 * Throttle\% - 1.6752)(1/16)(1/60) \tag{3}$$

This procedure was carried out for the 90.4% and 100% throttle conditions. The results are shown in Table 4.

Table 4 TSFC improvement at constant thrust for different engine conditions

Throttle Setting	Thrust at 0° vane angle (lbf)	Thrust at 15° vane angle (lbf)	Change in percent throttle to achieve 0° vane angle thrust	Change in TSFC (%)
90.4%	14.77	14.96	-0.98	-1.15
100%	16.72	17.11	-1.76	-1.98

The TSFC improvement at constant thrust is not as high, compared to the TSFC improvement at constant throttle position. Nevertheless, the improvement is still significant. As stated above, the current fuel flow relationship must be developed further to make it a function of pump voltage rather than a function of percent throttle. This work would lead to a more accurate TSFC estimate.

VI. Use Case Analysis

In order to analyze the viability of the new VIGV system, a potential use case is investigated. The Raytheon Coyote is a small, expendable, tube-launched, UAS. It has multiple use cases including as a hurricane hunter, a surveillance drone, and a counter-UAS solution [12]. The Block 2 version will be powered by a small gas turbine, probably similar to the JetCat P100-RX. An image of the Block 1 Coyote is shown below in Fig. 15.

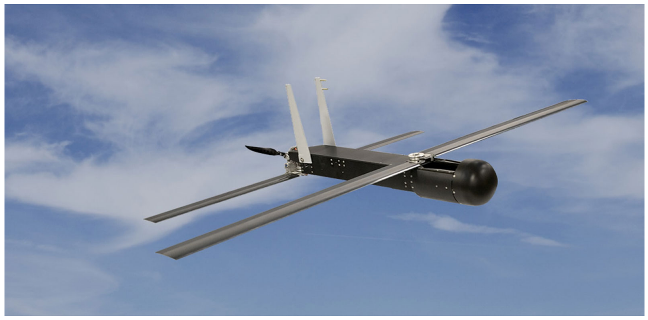


Fig. 15 Raytheon Coyote UAS [12]

The estimated endurance of the Block 1 Coyote is 1 hour and the cost is $20,000 per unit [13]. Since the Coyote is expendable, one mission minute is worth $333. If the VIGV system can improve the engine TSFC, at constant thrust, by 2.0%, the Coyote endurance will increase by 1.2 minutes. This is worth about $400.

A cost analysis is performed on the VIGV system assuming large scale production. Quoting estimates from 3DCompare were used to estimate the cost of the additive parts based on their volume [11]. Additionally, it was assumed only the bottom third of the outer casing would be printed out of thermoplastic. The results are shown below in Table 5.

Table 5 Cost breakdown of linear VIGV system

Part	Manufacturing Process	Material	Cost ($)
Inner Casing, Levers, Unison Ring	FDM Printing	PLA	10
12x IGV Blades	SLA Printing	Photopolymer Resin	26
Outer Casing	FDM Printing	$\frac{1}{3}$ ULTEM 1010 $\frac{2}{3}$ PLA	100
2x PQ-12R Linear Actuators	-	-	100
Assorted Hardware	-	-	40
		Total	**276**

Under the 2.0% TSFC improvement assumption, the VIGV system would be a worthwhile financial investment for the Raytheon Coyote. This TSFC assumption is in line with what was calculated from the prototype test data, however, this does not take into account the loss from the unoptimized inner and outer casing. If the aircraft already has an inlet, the VIGV system could be integrated with the inlet to provide benefits without the loss from the casings. Also, these estimations do not take into account the 23.5%, 0.56 pound, increase in engine weight.

VII. Conclusion

This study has investigated the design of a novel VIGV system installed on a JetCat P100-RX engine. Three potential designs were evaluated and two were physically manufactured to engineer a design that is low weight, simple to manufacture, precise, and cheap, relative to modern alternatives. The final design costs $276 and increases the engine weight by 0.53 pounds or 23.5%. The engine performance was measured at different throttle positions and different inlet guide vane angle positions to map the effect on the engine performance. Thrust data from the tests suggest that a 15° pre-whirl angle, at 100 % throttle, improves the engine thrust up to 2.3%. At constant thrust, TSFC is estimated to improve by 2.0%. Cost analysis suggests that the system has the potential to buy itself onto expendable UAS systems, like the Raytheon Coyote. This study has laid the groundwork for small gas turbine engine manufacturers to install VIGV systems on their engines. Future work can be done to test negative pre-whirl, optimize the casings to lower installation losses, and decrease system weight and cost.

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