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Mission Analysis and Operational Optimization of Adaptive Cycle Microturbofan Engine in Surveillance and Firefighting Scenarios

The current work focuses on mission-based evaluation of a novel engine architecture arising from the conversion of a microturbojet to a microturbofan via introduction of a variable speed fan and bypass nozzle. The solution significantly improves maximum thrust by 260%, reduces fuel consumption by as much as 60% through maintaining the core independently running at its optimum, and enables a wider operational range, all the meanwhile preserving a simple single spool configuration. Particularly, the introduction of a variable-speed fan enables real-time optimization for both high-speed cruise and low-speed loitering. In order to characterize the performance of the adaptive cycle engine with increased number of controls (engine speed, gear ratio, bypass opening), a component map-based thermodynamic study is used to contrast it against other similar propulsion systems with incrementally reduced input variables. In the following, a shortest path-based optimization is conducted over the locally minimum fuel consumption operating points, based on a set of gradient driven connectivity constraints for changes in gear ratio and bypass nozzle area. The resultant state transition graphs provide global optimum for fuel consumption at a thrust range in a given altitude and Mach flight envelope. Then, the engine model is coupled to a flight mechanics solver supplied with a conceptual design for a representative multipurpose unmanned aerial vehicle (UAV). Finally, the associated mission benefits are demonstrated in surveillance and firefighting scenarios. [DOI: 10.1115/1.4040734]

Introduction

Background. During the recent years, there is an increased interest in autonomous aerial systems. Market studies predict that the trends will continue in the near future with expected global unmanned aerial vehicle (UAV) market growth from \$13.22 billion in 2016 to \$28.27 billion by 2022 [1]. The forecasted compound annual growth rate for the period is 13.5%. The UAV propulsion systems market is also affected by this development. In 2016, the market generated \$363.8 Million in terms of revenue and it is expected to grow at a compound annual growth rate of 12.38% by 2022 [2]. This market expansion creates a rising influence on the propulsion industry and puts an emphasis on previously untackled challenges.

As the operational envelope of unmanned and remotely piloted air vehicles expands into the high subsonic and transonic speed range, the engine design process requires compromises in thrust, weight, fuel consumption, size, reliability, and manufacturing cost. Moreover, the engine requirements for multiple operating points, consisting of loitering, and high-speed flight during cruise are conflicting design criteria for an efficient propulsion system. In general, microturbojet engines may offer a simple design capable of providing high levels of thrust, but are marked by poor fuel consumption, hindering range. In contrast, larger platforms utilize turbofan engine architectures due to their greater propulsive efficiency.

Along these lines, the current research effort is focused around the development of a variable cycle microturbofan engine an existing microturbojet with less than 1 kN thrust. The project involves the conversion of a single spool microturbojet via integration of a fan, a continuously variable transmission (CVT), and a variable bypass nozzle (Fig. 1).

As the microgas turbine market suffers from restrained design costs, in order to shorten the design process to a minimum, the aspiration is to entail as few changes as possible to the core design. The solution, analyzed in the scope of this paper, significantly improves maximum thrust, reduces fuel consumption by maintaining the core independently running at its optimum, and enables a wider operational range, all the meanwhile preserving a simple single-spool configuration. Moreover, the introduction of a variable fan coupling would allow real-time optimization for several operational modes. Small gear ratio would yield a lower fan



Fig. 1 Illustration of an adaptive cycle microturbofan equipped with coupled turbofan with: (a) fan, (b) CVT, and (c) variable bypass nozzle

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bypass ratio, and therefore performance resembling a turbojet suitable for high speed flight, whereas large gear ratio would alter the engine cycle toward a modern turbofan, which provides improved fuel consumption during loitering and take-off. Thus, a small UAV equipped with this high-performance and costeffective variable-gear-speed turbofan would be able to operate efficiently in both "fly-fast" and "loiter" modes.

In addition, the acquired thrust increase translates into greater take-off weight, while independently varying bypass area and fan speed enables transonic flight and general reduction in fuel consumption. The combination of these effects yields an increase in range and loiter time. The aircraft architecture equipped with this adaptive engine can enable realization of unique missions that were prior unattainable or required different UAV propulsion systems. From an economical perspective, this will allow reduction in spare parts, as well as training costs of remote pilots on different engines. These unique characteristics allow penetration of UAVs into other markets such as search and rescue, disaster response, and firefighting missions.

In order to investigate the potential of this adaptive cycle microturbofan engine, a preliminary thermodynamic cycle analysis was conducted using an in-house MATLAB code, which was prior validated with commercial GASTURB software [3]. The maximal deviation of the fuel mass flow was 5.1% and 4.3% for the turbojet and the turbofan configurations, respectively. The purpose of the study was to simulate and contrast the steady-state performance of different microgas turbine configurations (conventional turbofan, fixed gear turbofan with variable bypass, variable gear, and bypass turbofan) with respect to the reference baseline microturbojet engine. In the scope of the current work, the toolbox is adjusted to model a larger engine using same algorithms and the gains associated with the CVT coupling and the variable bypass are re-evaluated for a larger platform in relevant, real-life missions.

Motivation. The thermodynamic feasibility of converting an existing microturbojet to an adaptive cycle microturbofan has already been demonstrated [3]. However, the potential benefits and operational limits of this novel concept have not been evaluated in representative platform requirements and conditions. In the scope of the current investigation, the engine maps are used to determine the optimal operating conditions in terms of variable bypass nozzle, core speed, and variable gear ratio for each altitude and Mach number pair. In the following, as the transition between different steady-state conditions is constrained by connectivity of intermediate gear ratios and nozzle areas, the operating lines are smoothed by optimization through "Shortest Path" algorithm. Then, the updated operating points with the connectivity restrictions are used conjointly with flight mechanics considerations to assess the UAV platform performance in realistic flight conditions. The benefits of the adaptive cycle microturbofan engine are highlighted for two separate UAV configurations, while addressing aerial surveillance and active firefighting missions.

Engine Performance Simulation

Algorithm Adjustments. At the first stage of simulation update, the available generic small-size turbojet component maps [4] are scaled up, according to Ref. [5], to match the size of a larger engine with maximal thrust of 650 N. Considering that the new cycle with the fan is to demand more work from the same turbine, increasing the inlet pressure to the core compressor would not only result in higher thermodynamic cycle efficiencies, but also enable extraction of additional power from the turbine.

Along these lines, typical large engines have a separate, dedicated booster stage in core stream for this purpose. However, such an approach is impractical for microturbines, especially considering our demand for maintaining the engine core architecture unchanged. Therefore, to include the desired positive effect, the hub of the fan rotor itself has to perform as a booster for the core stream. This gives rise to a nonconventional hub-loaded design, which counteracts the radial increase in tip speed yielding more work. Relaxing the blade tip through negative camber angle airfoils, the highly twisted rotor creates high axial velocity gradients opposing the radial direction. This configuration is dramatically different than the typical fan designs, such as those suggested in Ref. [6]. With the downstream stator hub becoming transonic and highly loaded, new design guidelines are required with additional emphasis on manufacturability and structural integrity. Through collaboration, this aspect of the project is addressed in Ref. [7]. The findings indicate that the practical limits of the fan core and bypass pressure ratios are 1.6 and 1.4, respectively.

This necessitates additional changes to the original MATLAB code. The core and the bypass streams are now evaluated via two different component maps with their own beta lines, corresponding to the core and the bypass regions, respectively. These charts are then connected by a shared corrected spool speed. At the time of the study, there were no available fan maps in open-literature particular for this scale. Therefore, the fan model from NASA's "Experimental Quiet Engine Program" was selected and modified for the intended application [8]. The core stream map was scaled to meet the mass flow rate requirements of the compressor in its design condition. The bypass map was scaled according to the maximum additional power that can be extracted from the turbine [5]. In off-design conditions, without physical separation of the core and bypass streams, spillage and mixing occur between the two streams. These effects cannot be neglected and the resultant pressure and temperature must be evaluated. As a first order of approximation, ignoring the mixing losses, the process is treated through mass averaging of the two quantities

$$TMP = \frac{\sum (\dot{m}_i TMP_i)}{\sum \dot{m}_i}, \quad PR = \frac{\sum (\dot{m}_i PR_i)}{\sum \dot{m}_i}$$

The scope of the current investigation assumes ideal transmission. Although in reality the efficiency of CVT gearboxes ranges between 94 and 96%, the effect of inefficiencies on thrust specific fuel consumption was shown to be less than 1% [3]. The variable bypass is similar in its design to a typical nozzle. It consists of stacked sleeves which change the exhaust area by altering their setting angle. As the engine architecture includes unmixed exhausts for the core and bypass streams, both nozzles are treated by a loss model, which correlates the discharge coefficient to nozzle area and pressure ratio.

The final augmented simulation algorithm used in the scope of this work is described in Fig. 2.

Simulation Results. This aforementioned algorithm is used to evaluate the benefits of the adaptive cycle turbofan. Thereby, the baseline turbojet is contrasted against fixed-gear/constant-bypass, fixed-gear/variable-bypass, and variable-gear/variable-bypass (adaptive) turbofans. Each architecture is simulated at the design condition for loitering flight (h = 5(km), M = 0.3). In the case of adaptive turbofan, the produced thrust and required fuel consumption are calculated for each gear ratio—bypass—RPM combination. The data sets that result in minimal fuel consumption at a given thrust level are selected as the engine operating condition. However, in the case of fixed-gear/variable-bypass engine, only the bypass value can vary as the shaft speed changes. The results are compared in terms of fuel consumption versus required thrust (Fig. 3).

As expected, conversion of turbojet into fixed-gear/fixedbypass turbofan effectively doubles the thrust potential of the engine. If the microturbine is then equipped with a variable bypass, the bypass ratio can be optimized toward most effective operating condition via bypass flow control, resulting in additional increase in operability (22% in thrust) at reduced fuel



Fig. 2 Turbofan simulation flowchart

consumption by 7%. Finally, when CVT gearbox is introduced into the engine and introduces an additional degree-of-freedom (DOF) to the system, the fuel consumption is further decreased for similar thrust levels, reaching up to 15% savings at 300 N thrust with respect to fixed-gear/variable-bypass turbofan. However, at the condition of maximal thrust, there are no advantages for CVT coupled engine as this constitutes the reference



Fig. 3 Fuel consumption versus thrust for various engine architectures at loiter condition (h = 5(km), M = 0.3)

Journal of Engineering for Gas Turbines and Power



Fig. 4 Fuel consumption versus thrust for various engine architectures at take-off condition (h = 0(km), M = 0)

"design" state of the fixed gear configuration, and the two engine architectures perform identically.

The adaptive cycle versatility is further explored by simulating the four engine types in take-off conditions (h = 0(km), M = 0)(Fig. 4). In this case, the fixed-gear/fixed-bypass turbofan is capable of increasing thrust by 87% to 1250 N when compared to the turbojet. In contrast, addition of the variable bypass increases the operability of the fan, and therefore, the fixed-gear/variablebypass turbofan still maintains higher thrust range (1700 N) at lowered fuel consumption by up to 11.3%. In this case, the addition of the variable gear further reduces the fuel consumption up to 15% for thrust output of 700 N.

Another typically occurring flight condition is cruise (h = 9(km), M = 0.9). Performance simulation outcomes in this mode are represented in Fig. 5. Now, conversion from turbojet to fixed-gear/fixed-bypass turbofan increases maximum thrust by 85%. Addition of the variable bypass yields 8% rise in thrust at improved fuel consumption. Finally, coupling of the CVT further reduces the fuel consumption by up to 7%.

For all engine operating conditions, performance simulations indicate similar fuel consumption trends that highlight the advantages of CVT and variable bypass nozzle. Considering the impact of CVT alone, when the gear ratio is augmented, the fan rotational speed decreases and it consumes less work. According to Euler turbomachinery equation, this directly translates into lower fan pressure ratio. Moreover, mass flow rate also decreases proportionally to the spool speed. Therefore, the fan map of a CVT coupled rotor portrays a spreading motion of the operating line, shifting both in pressure ratio and corrected mass flow rate. Moreover, behind the fan, the modified upstream pressure induced on the compressor changes the corrected mass flow rate imposing a shift on the operating point. However, the pressure ratio of the compressor remains the same. In addition to the effect of CVT, the variation of bypass nozzle area throttles the exhaust and



Fig. 5 Fuel consumption versus thrust for various engine architectures at cruise condition (h = 9(km), M = 0.9)

changes back pressure. Therefore, higher backpressure creates additional fan loading which is represented via increased pressure ratio. In turn, the mass flow rate reduces according to the negative slope of the simple stage compressor-loading characteristic. However, this process has almost no impact on the compressor operating point. Together, the two components (CVT and variable bypass nozzle) enable operation of the fan, independent of the engine core, ultimately allowing each component to operate at its local peak in efficiency island, yielding improved fuel consumption [3].

Clearly, the two variable bypass turbofans (with fixed or variable gearboxes) have thrust, fuel consumption, and operability advantage over the other configurations. Therefore, the following mission analysis consideration only includes fixed gear and variable gear turbofans, both with variable bypass nozzle. As these configurations have gearboxes of comparable size, the weight difference between them can be neglected. This will allow for a fair comparison between the two engines.

Transition Algorithm. When there are additional degrees-offreedom introduced into adaptive cycle turbomachines, a need for smooth transition between different steady-state operating points occur. However, the combinations of variables (such as core speed, variable gear ratio, and variable bypass nozzle area) for minimal fuel consumptions can result in technically optimal operating lines with sharp transitions. This discontinuity in component level operation is detrimental to overall engine performance and could even lead to complete engine shutdown. Demonstrating the issue, a representative case study focuses on the gear ratio transition between the 1100 and 1600 N thrust levels at take-off conditions (Fig. 6). A visible gap is present in gear ratios between 1380 N and 1400 N, red dots on the transition chart. A more desirable case would be a smooth transition (dashed line).

However, such arbitrary transitions are not realistic. Practically, the maximum allowed step can be limited within the simulation. The question is which initial thrust level and its locally optimal variable set should be selected as the starting point for a gradient induced transition limiter. However, this action does not define an optimal path which yields minimum aggregate fuel consumption.

In order to alleviate this problem, the system behavior over the entire operation range should be optimized in the presence of transition constraints. This approach includes construction of a surface consisting of all allowable gear ratio transition lines, each considering a different reference thrust level for the initiation of its





011010-4 / Vol. 141, JANUARY 2019

gradient-constrained change in variables. Therefore, each line has the optimal variable set for minimum fuel consumption only under its particular thrust level, defined as optimization parameter (Γ). Thus, the optimization parameter Γ is defined as reference thrust level for initiation of gradient-constrained transition path and has units of thrust. The surface is created through accumulation of all such transitions (Fig. 7). Absent of any operational transition constraints, ideal path would consist of traversing the diagonal line in chart (presented by straight diagonal line in Fig. 7). In order to



Fig. 7 Gear ratio (*a*), nozzle area (*b*), and core speed transition (*c*) optimization for operation range



Fig. 8 State-transition graph, where each state consists of a variable set in gear ratio, bypass nozzle area and core speed

find a global optimum in the presence of transition constraints, the "shortest path" method is implemented to find the most efficient, yet smooth operating line of the engine.

The simplest way to explain the shortest path method is to create an analogy to street traffic. Consider a situation where there is a need to travel from one junction to another through the streets of a large city. Naturally, one would want to travel the distance in shortest time possible. However, the time spent traveling through each single block differs based on current traffic load. Moreover, some of the streets might be completely blocked due to construction works. Therefore, minimization is conducted to find streets combinations that will ultimately result in shortest overall travel time. As a matter of fact, that is exactly how most modern traffic navigation systems work [9].

In this work, each "junction" represents one of the engine's working points. "Blocked streets" stand for improbable gear and bypass ratio transitions. "Block travel time" exemplifies the average fuel consumption between two adjacent working points. In the scope of this study, the impossible transition created in the blue line of Fig. 6 is taken as the reference for maximal gear ratio step.

To demonstrate the algorithm behavior, six hypothetical working conditions are charted in Fig. 8. In this transition graph, each node stands for possible operating condition—a unique combination of bypass value, core speed, and gear ratio. The rows describe constant Γ parameter and the columns depict constant thrust level *T*. The possible gear ratio and bypass transitions between the nodes are denoted by arrows with associated fuel cost. Average fuel consumption is denoted by f_{xx} (in arbitrary units), where the subscript indicates the transition direction. In this example, the transitions between points 1, 4, and 2, 5 are not allowed due to values larger than the criterion set for maximum gear ratio step limitation. In the case where the thrust is to be increased from T_1 to T_3 (from point 1 to 6), the transition $1 \rightarrow 2 \rightarrow 6$ is preferable to transitions $1 \rightarrow 5 \rightarrow 6$ or $1 \rightarrow 2 \rightarrow 3 \rightarrow 6$ due to reduced overall fuel consumption.

For the case study considered in Fig. 7, the state-transition diagram consists of 625 nodes with 332 allowable transitions. Artificial "start" and "end" nodes are defined without additional



Fig. 9 Adaptive cycle microturbofan engine operating line on (*a*) fan bypass map, (*b*) fan core map, (*c*) compressor map, (*d*) turbine efficiency map, and (*e*) turbine pressure ratio map

Journal of Engineering for Gas Turbines and Power



Fig. 10 Engine performance envelope across varying altitude and flight Mach number for: (*a*) thrust and (*b*) fuel consumption in fixed-gear/variable-bypass and variable-gear/variable-bypass turbofans

constraints and the optimization can begin at any state absent of penalties. The output of this analysis is the globally optimal thrust transition path from 1100 N to 1600 N that considers step-change constrains, green line in Fig. 7. The resolution of this graph (and therefore the solution) is only a function of the thrust discretization (ΔT) , and the final number of nodes is equal to $((T_{\text{max}} - T_{\text{min}})/\Delta T)^2$. Subsequently, this algorithm is applied to a more refined engine simulation, yielding a graph with 6400 nodes. For the take-off conditions, the globally optimal operating line with minimum aggregate fuel consumption is charted on the individual component maps (Fig. 9).

Conducting this analysis across an altitude range between 0 and 9 km and Mach range between 0 and 0.9, Fig. 10 presents the thrust and the globally optimized fuel consumption from the shortest path analysis for both fixed-gear/variable-bypass and variable-gear/variable-bypass turbofans, respectively. The top surface in Fig. 10(a) represents the maximal thrust level available at each operating point, while the bottom surface describes the idling condition. Figure 10(b) depicts the maximal fuel consumption that corresponds the top surface in Fig. 10(a). In reality, the intermediate thrust levels are also computed; however, they are not charted in order to improve clarity. Thereby, the fuel consumption can be evaluated for any required thrust at any particular altitude and flight velocity.

In order to ease computational load and to obtain reasonable calculation time, the points are discretized across the flight envelope with altitude and Mach steps of 1 km and 0.1, respectively. The intermediate regions are interpolated by a bicubic method, the validity of which is verified by additional simulations conducted at higher resolution (Fig. 11). The validation results are further summarized in Table 1. With average deviation of thrust specific fuel consumption of 0.8%, the integrity of the coarse grid solution is considered sufficient.



Fig. 11 Validation of the operating point interpolation

 Table 1
 Interpolation accuracy validation in terms of average thrust specific fuel consumption deviation

	Average deviation
Alt. 100 (m), Mach 0.15	0.5%
Alt. 5500 (m), Mach 0.35	0.8%
Alt. 8800 (m), Mach 0.88	0.8%

Flight Mechanics

The above-described method can be implemented to any engine cycle with multiple input variables, including fixed-gear/variable-bypass and variable-gear/variable-bypass turbofans. However, in order to discuss the potential benefits of a particular propulsion system on a platform, a mission analysis must be conducted. The inflight segments constitute four distinct regimes: (i) ascent, (ii) descent, (iii) low-speed loiter, and (iv) cruise. At each particular regime, the forces acting on the platform must be evaluated. Figure 12(a) presents the free body diagram during ascent, descent and cruise, whereas Fig. 12(b) captures the forces during circular loiter. In general, these forces are described as follows:

- Thrust force (*T*) is produced by the engine in the opposite direction to the mass flow leaving the engine. In the context of this work, the thrust force is assumed to always be in the direction of the flight.
- Drag force (*D*) is in the opposite direction to the relative motion of the platform. In the context of this work, the drag force is assumed to always be opposite to flight direction.
- Lift force (*L*) is produced by the wings of the aircraft and is always perpendicular to the oncoming flow direction. In the context of this work, the lift force is assumed to always be perpendicular to flight direction.
- Weight of the platform (W).

When no circular motion is present, combining the forces in the \hat{x} and \hat{z} directions yields the two basic equations of motion

$$D = T - W\sin(\gamma) \tag{1}$$

$$2L = W\cos(\gamma) \tag{2}$$

where γ is the climb angle. Assuming small values of γ (such that $\cos(\gamma) \approx 1, \sin(\gamma) \approx \gamma$) reduces the equations to

$$D = T - W \cdot \gamma \tag{3}$$

$$L = W \tag{4}$$

During continuous sustained turn, corresponding to the loiter segment of the mission, the wings of the aircraft are tilted at an

011010-6 / Vol. 141, JANUARY 2019



Fig. 12 Forces on the aircraft during: (*a*) unidirectional flight and (*b*) planar turn

angle ϕ . Therefore, in order to maintain constant altitude, the aircraft's weight must be balanced by the vertical component of the lift force. The horizontal component of the lift force matches the centripetal force required for the turn. Summarizing the forces perpendicular to and in the turning plane results in an additional set of equations:

$$L = W\cos(\phi) \tag{5}$$

$$L\sin(\phi) = \frac{WV^2}{gR}$$
(6)

where V is the flight velocity, R is the turn radius, and g is the gravity acceleration. To sustain the turn, the lift force and the weight ratio must be equal to $1/\cos(\phi)$. This value is known as the "load factor" (n).

The aircraft always needs to overcome the generated drag force. In the case of level flight, where climb angle γ is zero, the thrust has to be equal to drag (Eq. (4)). Therefore, the power available from the propulsion system must be equal to drag power

$$P_{\text{available}} = P_{\text{required}} \tag{7}$$

Any extra power supplied by the engine can be converted to gain altitude, or accelerate the platform, or turn. The ratio of the left-over power and the aircraft weight is defined as specific excess power (P_S)

$$P_{S} = \frac{P_{\text{available}} - P_{\text{required}}}{W} = \frac{(T - D)V}{W}$$
(8)

Specific energy (h_e) can be similarly defined as the ratio of the total aircraft energy (the sum of its kinetic and potential energies) and platform weight

$$h_e = \frac{E_{\rm TOT}}{W} = \frac{mgh + \frac{1}{2}mV^2}{W} = h + \frac{V^2}{2g}$$
(9)

where h is the flight altitude. As power is defined as the derivative of energy with respect to time, specific power becomes

$$P_S = \frac{dh_e}{dt} = \frac{dh}{dt} + \frac{V}{g}\frac{dV}{dt}$$
(10)

Usually, the lift and drag forces are represented by nondimensional coefficients, C_L and C_D , respectively, multiplied by dynamic pressure and reference area (S)

$$L = \frac{1}{2}\rho V^2 SC_L \tag{11}$$

$$D = \frac{1}{2}\rho V^2 S C_D \tag{12}$$

As the lift force is interchangeable with aircraft weight (Eqs. (4) and (5)), the value of the lift coefficient C_L is not relevant for the current study. The drag coefficient is generally described by two terms: parasitic drag (C_{D_o}) as a direct result of aircraft friction and induced drag (KC_L^2) due to lift forces [10]

$$C_D = C_{D_a} + K C_L^2 \tag{13}$$

The "drag-due-to-lift factor" (K) is defined as

$$K = \frac{1}{\pi Ae} \tag{14}$$

where A is the aspect ratio ($A = \text{wingspan}^2/S$) and e is Oswald's efficiency factor that provides correction due to nonelliptical lift distribution and flow separation. For swept-wing aircraft, e is empirically determined from Ref. [11], as

$$e = 4.61(1 - 0.045A^{0.68})\cos(\Lambda)^{0.15} - 3.1$$
(15)

where Λ is the sweep angle at the wing's leading edge. Now, the drag during flight can be evaluated by substituting Eq. (13) into Eq. (12), and the lift coefficient is eliminated by merging Eqs. (5) and (11). This leads to the general drag expression

$$D = \frac{1}{2}\rho V^2 S C_{D_o} + \frac{2Kn^2 W^2}{\rho V^2 S}$$
(16)

This equation can be conveniently split into two drag terms, contributing during level flight (where load factor n = 1) and turning drag (ΔD_n)

$$D = \underbrace{\frac{1}{2}\rho V^2 S C_{D_o} + \frac{2KW^2}{\rho V^2 S}}_{D_n = 1} + \underbrace{\frac{2K(n^2 - 1)W^2}{\rho V^2 S}}_{D_n \Delta D_n} \Delta D_n$$
(17)

The product of ΔD_n and the free stream velocity represents additional power necessary to perform the turn. Divided by the aircraft weight, the value can then be added to specific excess power, resulting in general specific power equation

$$P_S = \frac{dh}{dt} + \frac{V}{g}\frac{dV}{dt} + \frac{2K(n^2 - 1)W}{\rho VS}$$
(18)

This equation describes the specific power distribution between the three possible maneuver types. For the trivial case of level cruise, $P_S = 0$ as the platform maintains constant altitude, velocity, and direction. Climb is possible when P_S is positive, indicating that thrust value is higher than the drag. Conversely, descent

Journal of Engineering for Gas Turbines and Power

is an option when the drag force prevails and leads to negative P_S values. Finally, for the longitudinally asymmetric loiter, the additional P_S requirement can be represented via turn radius, which is more intuitive than fixing the load factor. Extracting turn radius from Eq. (6) and substituting it into Eq. (18) lead to another representation for the specific power

$$P_S = \frac{dh}{dt} + \frac{V}{g}\frac{dV}{dt} + \frac{2KV^3W}{\rho SR^2g^2}$$
(19)

Unlike the flight segments of cruise and altitude change, it is possible to control the thrust level for loitering turn regardless of the turn radius. At a given turn radius, the thrust is ideally minimized in order to reduce fuel consumption. For a sustained turn, as the thrust is equal to drag, the minimum drag velocity ($V_{D_{min}}$) can be evaluated from Eq. (17) as

$$\frac{dD}{dV} = 0 \to V_{D_{\min}} = \sqrt{\frac{2nW}{\rho S}} \sqrt{\frac{K}{C_{D_0}}}$$
(20)

Substituting $V_{D_{min}}$ back into Eq. (17) results in the minimum drag possible during loiter

$$D_{\min} = 2nW\sqrt{KC_{D_o}} \tag{21}$$

Therefore, knowing the turn radius during loiter, the two-equation system can be solved for the remaining unknowns—flight velocity and load factor

$$\begin{cases} V = \sqrt{\frac{2nW}{\rho S}} \sqrt{\frac{K}{C_{D_o}}} \\ R = \frac{V^2}{g\sqrt{n^2 - 1}} \end{cases}$$
(22)

Implementation of this method allows for evaluation of a UAV platform's aerodynamic behavior at any point along its mission path. Based on this framework, the thrust requirements of the platform are computed during the flight at discrete time steps Δt (Fig. 13). For any mission profile, the code evaluates specific power, flight velocity, weight, and drag force during each timestep. Then, the thrust demand for requested maneuver can be calculated from

$$T = \frac{P_S W}{V} + D \tag{23}$$

During climb and descent, the ground distance (ΔGD) is calculated based on average velocity of two adjacent time intervals— $\Delta GD = \Delta t \cdot V_{avg}$. Comparably, the change in altitude is calculated from $\Delta h = (dh/dt) \cdot \Delta t$. Any acceleration or climb between major flight segments is performed at maximum available thrust in order to shorten transition period to minimum. Fuel depletion is



Fig. 13 Flight mechanics algorithm

011010-8 / Vol. 141, JANUARY 2019

evaluated as a product of the time-step and the engine's fuel consumption at the requested thrust for a particular altitude and flight velocity. Therefore, the engine performance can be evaluated for all points in the mission by portraying thrust and the globally optimized fuel consumption from the shortest path analysis for both the fixed-gear/variable-bypass and variable-gear/variable-bypass turbofan configurations (Fig. 10).

Unmanned Aerial Vehicle Design. To evaluate the prior described aerodynamic properties and complement the engine simulation with flight mechanics data, preliminary design of a representative flying platform is carried out. The main challenge is selection of an aerial vehicle that is relevant in a wide gamut of scenarios. Although most modern UAVs have glider-like shapes and are designed for maximal endurance at slow speeds, Northrop Grumman's X-47B UAV is capable of both fast subsonic flight and slow loiter [12]. Therefore, its shape is considered as the baseline geometry, with twin engine configuration in order to increase the operational range. The maximal thrust of each microturbofan is evaluated via the engine model as ~1500 N at take-off. Now, the gross take-off weight of the UAV can be estimated. Typical value for thrust to weight ratio (T/W_o) varies from 0.25 to 0.4 for jet powered aircrafts [10]. The assumption of $T/W_{o} = 0.32$ is sufficient for the sake of propulsion system comparison. This results in gross UAV weight of 955 kg.

The empty weight fraction of the vehicle can be calculated according to $W_e/W_o = AW_o^c$ [10]. Since the design is based on combat UAV, A and c are specified as 1.53(1/N) and -0.16, respectively. Substituting these values into empty weight fraction equation yields $W_e/W_o \approx 0.5$. Now, knowing the limits of UAV weight allows for the assessment of the aircraft's payload and fuel capacity.

To further approximate the platform dimensions, wing loading during take-off is assumed to be $W/S = 127(kg/m^2)$ -a general value for twin-engine aviation [10]. This results in wing area of $S = 7.52(m^2)$. Using the available footage and published dimensions of X-47B, and applying the calculated mass fraction and wing area values, a representative model that includes possible internal layout is generated (Fig. 14). Using this schematic, the wetted area and the sweep angle of the leading edge are determined as $S_{wet} = 16.46(m^2)$ and $\Lambda_{avg} = 45(deg)$, respectively. Sweep angle is then used to calculate Oswald's efficiency factor e(Eq. (15)) and drag due to lift factor K (Eq. (13)). Knowing wetted area makes it easy to predict parasitic drag coefficient C_{D_o} via "Equivalent Skin Friction Method"— $C_{D_o} = C_{f_e}(S_{wet}/S)$. In this case, the equivalent skin friction coefficient C_{f_e} is taken as 0.003 [10]. Now, all the relevant properties needed for the detailed mission analysis are known and summarized in Table 2.

Mission Analysis

Unmanned aerial vehicles are widely used around the globe during variety of natural disasters. As they become essential



Fig. 14 UAV platform layout



Fig. 15 Surveillance mission profile

assistants that provide relief services in catastrophic events, it would be of particular interest to contrast the performance of platforms that include fixed-gear/variable-bypass and variable-gear/ variable-bypass turbofan configurations as their propulsion systems. Two distinct scenarios are explored: (i) surveillance and monitoring and (ii) active firefighting.

Surveillance Mission. For the analysis of the surveillance mission, a 1000 km remote location is considered to suffer from a natural disaster. The flight path during operation is described in Fig. 15. At first, the UAV ascends to an altitude of 9 km at constant Mach of 0.5. Then, it cruises toward target destination at Mach 0.9. As it approaches its objective, the aircraft descends for 30 km at constant Mach of 0.5 to an altitude of 5 km and starts loitering above the disaster site with a 5 km turn radius. Then, when the fuel reaches the no-return threshold, the platform follows a similar route to the airfield for refueling. During the last 20 km, it will slow down to Mach number 0.3 for safe landing. In order to maximize loiter time, the payload bays are replaced with additional fuel tanks. The goal of the mission is to stay on target for as long as possible.

The thrust and fuel consumption profiles can be charted throughout entire mission based on the detailed flight mechanics model described above. For this mission, the thrust profiles are created for both engine types powering the same UAV platform (Fig. 16). Highest levels of thrust are required during the take-off and as the altitude increases, the thrust demand declines. During the cruise and loiter, thrust demand continues to decrease as UAV loses its weight due to fuel burning. Descent starts from gliding, where engines work in idle mode. This results in sharp plunges in thrust, which are observed after 55 min (at a distance of 970 km from base) and 360 min (at a distance of 100 km from base) for the fixed-gear turbofan. Comparatively, in the case of variablegear turbofan, the second descent occurs after 420 min of flight (at a same distance-to-base). With the altitude loss, as the UAV needs to keep the prescribed Mach number, the thrust levels rise once again. This most prominently manifests itself as a slight thrust increase during the final descent toward landing (last $\sim 15 \text{ min of}$ the mission). Additional thrust spikes are observed after 310 min and 370 min for fixed-gear and variable-gear turbofans, respectively. These peaks correspond to ascent from loitering to cruise



Fig. 16 Thrust profiles for surveillance mission with fixedgear/variable-bypass and variable-gear/variable-bypass turbofans with respect to mission time in (min) and distance-to-base in (km)



Fig. 17 Fuel consumption profiles for surveillance mission with fixed-gear/variable-bypass and variable-gear/variablebypass turbofans with respect to mission time in (min) and mission distance-to-base in (km)

regime en route back to base. This maneuver is executed with maximal available thrust.

Expectedly, the fuel consumption correlates positively with the thrust requirements (Fig. 17). The ascent is conducted at maximum thrust (in reference design condition of the fixed gear engine), and therefore the performance of the two engines is identical. Moreover, as the time required for descent is negligible when compared to overall mission duration, there are no significant advantages arising from the functionality of variable transmission. Conversely, there is clear improvement in fuel consumption during the lengthy cruise and loiter segments of the mission. As the fuel consumption for CVT coupled engine configuration is lower at comparable thrust, the UAV with only variable bypass turbofan engine is forced to return to base earlier due to fuel depletion. The UAV powered by variable-gear/variable-bypass turbofan is able to stay 60 min more above the target location, resulting in 20% additional loiter time.

Journal of Engineering for Gas Turbines and Power

Firefighting Mission. Designed as a multipurpose platform, such a UAV can also serve as crucial aid in putting out forest wildfires, as the vehicle's payload bays are capable of holding up to 365 kg of water. Bush and forest fires became a significant issue during recent years, and in order to successfully respond to this phenomenon, there is an urgent need to react to even the smallest ignition epicenter. In remote areas, only aviation can handle this task, but sending large and heavy water-tankers to put out small fires is not a cost-effective policy. Moreover, due to safety regulations, manned aircrafts are limited to operations during daylight and the resulting night-break can nullify the firefighting efforts. Therefore, cheap, small-size UAVs present a viable solution to the problem. Moreover, fleets of small UAVs will have a benefit over a single large tanker due to their ability to spread water in a more efficient way.

Consider a hypothetical firefighting mission, lasting for six hours of darkness, 300 km away from nearest airfield on 970 m high forested hill. Such scenario could involve both a leading surveillance UAV and a fleet of three mule firefighters, blue and green lines in Fig. 18, respectively.

The leading surveillance UAV ascends to 5 km altitude at Mach 0.5 and cruises toward the fire region. Then, it loiters above the location for six hours providing relevant information and guiding the firefighting fleet. At the end of the mission, it returns back to the airfield at constant velocity, descending fort the last 30 km. The firefighter UAVs ascend to 3 km altitude and proceed to mission location at constant Mach of 0.5. Then, they slow down to Mach 0.3 and descend the last 30 km to 1 km altitude before dropping their water payload. Finally, they return to base in order to refuel and resupply. As it takes the firefighter UAV about half an hour to reach the burning target, each UAV can complete six full rounds during the mission duration. In the meantime, the surveillance UAV remains above the target the entire duration. The goal of this analysis is to measure the total amount of fuel consumed during the mission.

Similar to the previous mission analysis, the thrust and fuel consumption for both UAV types are described in Figs. 19 and 20, respectively. After first half hour, the surveillance UAVs are positioned above the fire and the mule UAVs are sent into action. The mule's cruise toward the fire and back to base takes half an hour per direction and is indicated by thrust level spikes. Return cruise periods are characterized by lower thrust levels due to reduced weight after water drop-off. Once again, the most noticeable fuel consumption difference is observed during loiter and cruise for both mule and surveillance UAVs.

As depicted in Fig. 19, the variable-gear equipped UAVs are lighter and require lower levels of thrust. This is an artifact of the



Fig. 18 Firefighting mission profile for the surveillance and mule UAVs (higher and lower altitudes, respectively)

011010-10 / Vol. 141, JANUARY 2019



Fig. 19 Thrust profiles for firefighting mission by surveillance and mule UAVs either equipped with fixed-gear/variable-bypass or variable-gear/variable-bypass turbofans with respect to mission time in (min) and distance-to-base in (km)



Fig. 20 Fuel consumption profiles for firefighting mission by surveillance and mule UAVs either equipped with fixed-gear/ variable-bypass or variable-gear/variable-bypass turbofans with respect to mission time in (min) and distance-to-base in (km)

higher-efficiency propulsion system, which carries lower amount of total fuel onboard for the same mission time. The charts show clear advantage of the variable-gear/variable-bypass microturbofan engines, as the total fuel consumption by the fleet reduces by 12.2% for the entire mission, totaling a fuel saving of 268 kg.

Summary

The current research effort focuses around detailed missionbased investigation of a novel adaptive cycle microturbofan engine, converted from a microturbojet via addition of a CVT coupling and a variable bypass. Combining the benefits of a fan and a core stream booster, an original hub-loaded fan design is considered as part of the advanced investigation. This not only

yields higher thermodynamic cycle efficiency, but also enables the extraction of additional power from the turbine. In following, the benefits of the conceptualized propulsion system are presented on a realistic platform for a variety of flight conditions during various conceivable missions.

As a first step, a component map-based thermodynamic study is conducted for the baseline turbojet and contrasted against fixed-gear/constant-bypass, fixed-gear/variable-bypass, and variable-gear/variable-bypass turbofans. At the take-off condition, the reference turbojet has thrust rating of 650 N. The addition of a fixed gear fan increases the obtainable thrust level to 1250 N. When the variable bypass feature is added to the engine architecture, the maximum thrust is further increased to 1700 N, with reduced fuel consumption up to 11%. Finally, when the engine is equipped with a continuously variable transmission between the core and the fan, the fuel consumption is further reduced by up to 15% for operating conditions with less than maximal thrust. Overall, the variable bypass turbofan engines (with either fixed or variable transmission) resulted in highest thrust rating, enabling further comparison based on fuel consumption.

However, the additional degrees-of-freedom introduced into the cycle with the inclusion of the CVT and the bypass result in a nontrivial requirement for smooth shift between different operating points. Therefore, a novel method was developed to ensure desirable transition between different turbine control states. Based on the application of the "shortest path" algorithm, the new method charts the transition path in terms of aggregate minimum fuel consumption, given connectivity, and smoothness constraints.

Finally, the simulation framework is extended to include platform-based analysis by detailed flight mechanics evaluation on a conceptual multi-purpose UAV design. The performance of the UAV powered by the two variable bypass engine architectures is assessed under realistic scenarios. For these surveillance and firefighting missions, the continuously variable transmission geared microturbofan engine displays superior performance, adding an extra hour of loiter and saving 12% of fuel with respect to the fixed-gear engine. Moreover, these scenarios would traditionally require two different engines with distinct design points. However, the analysis demonstrates that the adaptive cycle configuration is highly efficient regardless of the mission, eliminating the need for development of tailor-made engines.

Conclusions

In the scope of this investigation, the variable-gear/variablebypass microturbofan engine configuration demonstrates itself as an efficient and versatile propulsion system, which can be derived from an existing microturbojet.

Lessons Learned

- (a) Conversion of a microturbojet into fixed-gear/fixed-bypass microturbofan significantly increases the engine thrust level. During loiter, take-off and cruise, the thrust improvement is 125%, 87%, and 85%, respectively.
- (b) Introduction of variable bypass nozzle results in further thrust level increase and reduction of fuel consumption. Thrust gains are 22%, 36%, and 8% for loiter, take-off and cruise conditions, respectively. Fuel consumption decreases by 7% in loiter and cruise. During take-off, the fuel consumption drops by 11.3%.
- (c) Further improvement is achieved by integration of CVT into the engine architecture. This leads to fuel consumption improvement by up to 15% in loiter and take-off conditions. In cruise, the savings in fuel consumption are up to 7%.
- (d) Beyond the control of thrust via fuel mass flux in a conventional engine, there are added degrees of freedom introduced by the inclusion of CVT and variable bypass. In

order to chart the transition path in terms of aggregate minimum fuel consumption, given connectivity and smoothness constraints, a specialized optimization method, based on "shortest path" algorithm, can be implemented toward a globally optimal solution.

- (e) A detailed thermodynamic model can be integrated into a conventional flight mechanics framework, in order to assess and demonstrate the platform benefits of different engine architecture derivatives.
- (f) In a surveillance mission, when the distance to observed location is 1000 km, UAV equipped with variable-gear/ variable-bypass engine can sustain an additional 1 h loiter time, yielding 20% improvement over fixed-gear/variablebypass configuration. In firefighting mission, which involves both surveillance and mule UAVs, the variablegear/variable-bypass configuration demonstrates fuel saving of 12%.
- (g) Improving thrust and fuel consumption, the variable-gear/ variable-bypass microturbofan engine has superior performance for all considered scenarios. Suitable in a vast set of applications, this configuration can fulfill a broad spectrum of current demands in the rapidly growing propulsion industry.

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Nomenclature

Symbol Description

- A = aspect ratio
- $C_L =$ lift coefficient
- $C_D = \text{drag coefficient}$
- C_{D_o} = parasitic drag coefficient
- C_{f_e} = equivalent skin friction coefficient D = drag (N)
- E = energy(J)
- GD = ground distance (m)
- K =drag-due-to-lift factor
- L = lift force (N)M = Mach number
- e = Oswald's efficiency factor
- f = fuel consumption (kg/s)
- $g = \text{gravity acceleration } (\text{m/s}^2)$
- h =altitude (m)
- h_e = specific energy (m)
- $\dot{m} = \text{mass flow rate (kg/s)}$
- n = load factor
- P = power(W)
- PR = pressure (Pa)
- P_s = specific excess power (W/N)
- R = turning radius (m)
- S = reference wing area (m²)
- T =thrust (N)
- TMP = temperature (K)
 - V = flight velocity (m/s)
 - W =weight (N)
 - $W_e = \text{empty weight (N)}$ $W_o = \text{gross weight (N)}$
 - Γ = optimization parameter—reference thrust level for initiation of gradient-constrained transition (N)
 - $\Lambda =$ wing sweep angle (deg)
 - $\gamma = \text{climb} \text{ angle} (\text{deg})$

Journal of Engineering for Gas Turbines and Power

 $\rho = \text{density} (\text{kg/m}^3)$

 $\phi = \text{roll angle (deg)}$

Abbreviations Description

CAGR = compound annual growth rate

- CVT = continuously variable transmission
- UAV = unmanned aerial vehicle

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