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Micro-Turbojet to Turbofan Conversion Via Continuously Variable Transmission: Thermodynamic Performance Study

In this study, the viability, performance, and characteristics of a turbojet-to-turbofan conversion through the use of a continuously variable transmission (CVT) are investigated. By an in-house thermodynamic simulation code, the performance of the simple cycle turbojet, a direct shaft joined turbofan, and a CVT coupled turbofan with variable bypass is contrasted. The baseline turbojet and turbofan findings are validated against a commercial software. The comparison indicates high quantitative agreement. Analyzing the results of the turbofan engine equipped with a variable bypass and CVT, it is observed that both the thrust and the efficiency are increased. The augmented thrust is observed to be an artifact of enhanced component matching and wider operational range introduced by variable bypass capability. On the other hand, the introduction of CVT contributes to the reduction in fuel consumption. Therefore, the current research suggests that adaptation of a micro-turbojet into a variable cycle micro-turbofan will greatly improve the performance and efficiency of existing engines, in addition to providing a pathway toward extended use in various applications. [DOI: 10.1115/1.4034262]

Keywords: variable cycle engine, continuously variable transmission, turbojet–turbofan conversion, thermodynamic cycle modeling

Introduction

As gas turbines are becoming increasingly complex, the apex of engine efficiency seems to be fast approaching. In an attempt to further improve gas turbines, new technologies are explored in an ever-growing effort to increase thrust-to-weight ratio and minimize thrust specific fuel consumption (TSFC), all the while reducing the overall cost of the engine development.

Motivation. Even though most gas turbine classes are showing great advancements in recent years, in terms of both efficiency and performance, there is one class of engines that seems to have been left behind—the class of microgas turbines (under 1 kN of thrust). Surveying the market of microgas turbines compatible with unmanned air vehicles (UAVs), the selection of engines in this category consists mostly of turbojets, with a distinct lacking of turbofans (Fig. 1).

While turbojet engines may offer a simple design capable of providing high levels of thrust, they are usually marked by poor fuel consumption; turbofan engines, on the other hand, while being more complex and expensive, can provide similar or higher levels of thrust at a greater efficiency. In order to improve the performance while reducing the TSFC, which is considered to be the most influential engine characteristic relating to efficiency [1], the sensible solution is to introduce a turbofan into the microgas turbine category. If an efficient, well-performing, affordable turbofan can be successfully designed, the application of microgas turbines may be expanded into fields for which were prior considered unsuitable. **Concept.** The design process of a new engine usually entails high cost and prolonged development period. Tradeoffs are often required in aspects such as thrust, weight, and fuel consumption. These compromises are especially noticeable in the market of microgas turbines, which typically suffer from restrained research and development costs, and inherently low component efficiencies.

To maintain the distinct advantages of engines equipped with bypass, while reducing the development cost and time to a mere fraction of those of a new engine [1], a turbofan design derived from a pre-existing turbojet may offer a good concession.

While the concept of turbojet-to-turbofan conversion is not a new one, and has been implemented many times in the past [2], the effort usually requires a substantial amount of redesign or considerable changes to the core stream (such as additional lowpressure (LP) spools, aft-fan on the LP turbine, etc.) To reduce cost and shorten the design process to a minimum, the current aim



Fig. 1 Existing engines of less than 1000 lbs of thrust. (Reproduced with permission from Nelson and Dix [1]. Copyright 2002, 2003 by Institute for Defense Analyses.)

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is to entail as few changes to the core design as possible—this primarily refers to the addition of components to the core.

To achieve this goal, the investigation utilizes an old concept, which has only recently matured—a continuously variable transmission (CVT). A CVT is a type of gearbox that can continuously vary the transmission ratio to any value between two prescribed boundaries. The CVT would negate the need for a slow turning low-pressure spool to power the fan, and enable maintaining a simple single spool configuration while offering direct control over the fan speed, independent of the core revolutions per minute (RPM). The use of such a transmission would enable operation in a wider gamut of conditions, enhance performance, and ease the fan to core matching process.

By means of a thermodynamic performance analysis, the current study is focused on investigating the merits of a CVT coupled turbofan with variable bypass nozzle. The modeling procedure depicted in this paper leans on the thermodynamics outlined in Ref. [3]. Based on the described equations, there have been previous efforts on calculating the performance of turbojet and turbofan engines [4]. The adaptation of the transient and steady-state models to simple cycle one-spool microjet engine environment was prior demonstrated in Refs. [5] and [6], respectively; the current effort utilizes core engine component maps from these investigations. With the publically available fan maps provided in Ref. [7], and based on the scaling procedure described in Ref. [8], the hypothetical performance of a relevant micro-turbofan can be conceptualized. Moreover, the appropriate modeling scheme of variable area bypass nozzle, along with its cycle benefits, has been prior documented in Ref. [9]. Building upon the existing literature, the present contribution addresses the scientific void in adaptive engine development via CVT coupling of a fan with a micro-turbojet, in the presence of variable bypass nozzle.

In order to accentuate the conceptual benefits of a CVT coupled turbofan, this investigation assumes an ideal transmission (i.e., no losses and no reference to weight). Moreover, considering that typical transmission efficiency values vary between 94% and 96% for a broad range of operating conditions, modeling of the mechanical drive is of secondary importance. The error associated with this assumption is estimated to be less than $\sim 1\%$ in thrust specific fuel consumption.

In the scope of the current research effort, the considered engine configurations are: turbojet, fixed-gear turbofan, CVT geared turbofan, and CVT geared turbofan with a variable bypass nozzle. For a typical altitude and flight speed, the investigation contrasts the thrust and TSFC on an engine line for each of the alternatives. Adaptation of a micro-turbojet into a variable cycle micro-turbofan can greatly improve the performance and efficiency of existing engines, in addition to providing a pathway toward extended use in various applications.

Simulation—Cycle Modeling

In order to fully investigate the turbojet-to-turbofan conversion process, a thermodynamic cycle analysis is conducted. The current modeling effort is carried using an in-house MATLAB code with the purpose of simulating and comparing the steady-state performance of different gas turbine configurations. The two baseline turbojet and turbofan configurations are validated against a commercial simulator (GASTURB 11). In the following, more advanced cycles (such as a CVT turbofan with variable bypass nozzle) are subsequently modeled.

Gas Modeling. For the gas turbine model to be accurate, in addition to correct equations describing the cycle, the exact values of the gas properties through the engine and an accurate representation of component maps had to be obtained. This simulation treats the flow as a semiperfect gas, yielding realistic gas properties. This assumption enables the use of the ideal gas law and stipulates that the specific heat capacity may be a function of temperature but not pressure

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ideal gas law:
$$P = \rho RT$$
 (1)

semiperfect gas:
$$C_p = f(t)$$
 (2)

$$C_p \neq f(P) \tag{3}$$

$$\left(\frac{\partial h}{\partial P}\right)_{T=\text{const}} = 0 \tag{4}$$

Following this assumption, the polynomial coefficients provided in Ref. [10] were used to calculate the thermodynamic properties of the working fluid. These properties are a function of the fuel type, the fuel-to-air ratio, and the temperature of the flow.

Component Maps. Real engine component maps are often undisclosed for proprietary reasons. Instead, generic component maps that match the behavior of small gas turbines are used [11]. The compressor and turbine performance can be seen in Figs. 2(a)-2(c).

When necessary, as there are no fans specifically designed for this application, publically available fan model from NASA's "Experimental Quiet Engine Program" is selected and subsequently scaled for the intended application [12]. This process is guided by the similarity analysis and Buckingham Π theorem.

The first step in the application of the similarity principle is the selection of the dimensional physical quantities that affect the fan performance, in this case mass flow (\dot{m}), inlet total pressure and temperature (P_{01} , T_{01}), exit total pressure (P_{02}), rotation speed (N), diameter (D), and gas properties (γ , R, ν). Using the Buckingham Π theorem with the selected dimensional quantities provides the subsequent nondimensional performance groups

$$\prod_{1} = \frac{\dot{m}\sqrt{RT_{01}}}{P_{01}D^2}$$
(5)

$$\prod_{2} = \frac{P_{02}}{P_{01}}$$
(6)

$$\prod_{3} = \frac{ND}{\sqrt{\gamma R T_{01}}} \tag{7}$$

$$\prod_{4} = \frac{ND^2}{\nu} \tag{8}$$

For a scaled component to be considered similar to its source, both sets of Π groups should yield the same products [7]. When a fan is geometrically scaled (i.e., all dimensions are scaled by the same factor), and if Reynolds number effects are neglected (Eq. (8)), the following relations can be deduced:

$$\dot{m} \propto D^2$$
 (9)

$$N \propto \frac{1}{D} \tag{10}$$

In the scope of the current study, Fig. 3 depicts the resulting scaled fan map employed when necessary.

Turbojet Modeling. The turbojet model constitutes the basis of the incrementally advanced modeled cycles. In order to thermodynamically characterize the system's performance, each engine station has to be considered independently. A schematic drawing of a turbojet engine, along with the corresponding station numbering, is shown in Fig. 4.

The static ambient temperature and pressure are based on the values of standard atmosphere model. The corresponding total



Fig. 2 Baseline turbojet component maps: (*a*) compressor, (*b*) turbine efficiency, and (*c*) turbine mass flow rate

temperature and pressure are then calculated using the isentropic relations

ambient conditions:
$$T_a = T_{\rm sl} - 0.0065H$$
 (11)

$$T_{0a} = T_a (1 + 0.5(\gamma_a - 1)M_a^2)$$
(12)

$$P_a = P_{\rm sl} (1 - 0.0065 H/T_{\rm sl})^{5.2561} \tag{13}$$

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Fig. 3 Scaled fan map

$$P_{oa} = P_a (1 + 0.5(\gamma_a - 1)M_a^2)^{\gamma_{\gamma} - 1}$$
(14)

Considering that there is no work and assuming negligible heat transfer in the diffuser, the total temperature does not change across it. However, the total pressure is slightly reduced due to losses associated; this is characterized by the diffuser efficiency

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diffuser:
$$T_{02} = T_{0a}$$
 (15)

$$P_{02} = P_{0a}\eta_d \tag{16}$$

During the compression process, the total temperature and pressure increase. This process is nonideal, and the compressor losses are expressed by the compressor efficiency (η_c)

compressor:
$$T_{03} = T_{02} \left[\frac{1}{\eta_c} \left(\frac{P_{03}}{P_{02}}^{\frac{\gamma-1}{\gamma}} - 1 \right) + 1 \right]$$
 (17)

$$\eta_c = \frac{h_{03s} - h_{02}}{h_{03} - h_{02}} \tag{18}$$

Representing the first law of thermodynamics in the combustor, Eq. (19) can be derived. The combustion efficiency is described by an empirical model that relies on known design point values, and calculated off-design efficiency, based on the combustor loading parameter (Ω)

combustor:
$$(\dot{m}_{air} + \dot{m}_f) \cdot h_{04} - \dot{m}_{air} \cdot h_{03} = \dot{m}_f \dot{Q}_r \eta_b$$
 (19)

$$\eta_b = 1 - (1 - \eta_{b,dp}) (\Omega/\Omega_{dp})^{P_l}$$
⁽²⁰⁾

$$\Omega = \frac{\dot{m}_{air}}{P_{03}^{1.8} \cdot \exp\left(\frac{T_{03}}{300}\right) \cdot \operatorname{Vol}_{comb}}$$
(21)

The nonideal expansion process in the turbine is described by Eqs. (22) and (23). It entails a drop in both total pressure and temperature through the turbine. A power balance between the turbine and the compressor is represented by Eq. (24)

turbine:
$$\eta_t = \frac{h_{04} - h_{05}}{h_{04} - h_{05s}}$$
 (22)

$$\frac{(T_{04} - T_{05})}{T_{04}} = \eta_t \left[1 - \frac{1}{\left(\frac{P_{04}}{P_{05}}\right)^{\frac{\gamma-1}{\gamma}}} \right]$$
(23)

$$\dot{m}_{\rm air}(h_{03} - h_{02}) + P_{\rm out} = \eta_m (\dot{m}_{\rm air} + \dot{m}_f)(h_{04} - h_{05})$$
 (24)

The mass flow output from converging propelling nozzle is calculated by Eq. (26), where C_D is the discharge coefficient related to the nozzle pressure ratio and angle. Based on a choked flow condition, the static exit pressure can be determined. Calculating the critical pressure enables the static exit pressure to be set accordingly

propelling nozzle:
$$\eta_n = \frac{h_{07} - h_9}{h_{07} - h_{9s}}$$
 (25)

$$\dot{m}_9 = C_D \cdot \frac{P_e}{RT_e} \cdot U_e A_e \tag{26}$$

In order to reach a steady-state, the simulation algorithm for the turbojet model requires a nested iterative process. An inner iterative loop is used to satisfy the compressor-turbine mass flow and power balances, and an outer iterative loop is implemented to satisfy the diffuser-nozzle mass flow balance. The algorithm, as described in Fig. 5, consists of (a) an input of flight conditions, engine data, and component maps; (b) interpolation of component maps using N, β coordinates; (c) selection of a compressor β line as a parameter for the outer iteration loop; (d) reading of the compressor map and extraction of mass flow, pressure ratio, and efficiency; (e) selection of T_{04} as a parameter for the inner iteration loop; (f) solution of the combustion chamber equations; (g) solution of the turbine equations and reading of the turbine map; (h) matching of gas generator mass flow for inner loop convergence; and (i) matching of inlet to nozzle mass flow for outer loop convergence. Once the algorithm fully converges, the temperature and pressure along various engine stations, as well as the system performance, are fully determined for a given flight condition.

Fixed-Gear Turbofan Modeling. In order to incorporate the addition of a fan into the thermodynamic cycle simulation, the following equations characterize the fan component performance and the modified shaft power balance:

fan:
$$T'_{03} = T_{02} \left[\frac{1}{\eta_F} \left(\frac{P'_{03}}{P_{02}}^{\frac{\gamma-1}{\gamma}} - 1 \right) + 1 \right]$$
 (27)

$$\eta_F = \frac{h'_{03s} - h_{02}}{h'_{03} - h_{02}} \tag{28}$$

turbine:
$$\dot{m}_{air_{fan}}(h'_{03} - h_{02}) + \dot{m}_{air_{core}}(h_{03} - h_{02c}) + P_{out}$$

= $\eta_m(\dot{m}_{air_{core}} + \dot{m}_f)(h_{04} - h_{05})$ (29)

A schematic drawing of a turbofan engine, along with the corresponding station numbering, is shown in Fig. 6.

Closely resembling the algorithm used by the turbojet simulation, the turbofan cycle expands the model to include a fan and a bypass stream. Moreover, it satisfies the mass flow balance between the inlet and both the core and bypass nozzle. The main steps of the algorithm are portrayed in Fig. 7: (a) an input of flight conditions, engine data, and component maps; (b) interpolation of component maps using N, β coordinates; (c) selection of core RPM and gear ratio; (d) selection of a fan β line as a parameter for the outer iteration loop; (e) reading of the fan map and extraction of mass flow, pressure ratio, and efficiency; (f) solution of the bypass stream; (g) reading of the compressor map; (h) selection of T_{04} as a parameter for the inner iteration loop; (i) solution of the combustion chamber equations; (j) solution of the turbine equations and reading of the turbine map; (k) matching of gas generator mass flow for inner loop convergence; and (l) matching of core inlet to core nozzle mass flow for outer loop convergence.



Fig. 4 Schematic drawing of a turbojet



Fig. 5 Turbojet simulation flowchart

As the fan map used for the simulation is obtained from the scaling process, the choice of gear ratio becomes an independent variable. In this regard, a constraint of fan tip Mach number of 1 is imposed at 100% core RPM. Thereby, the fan RPM is deduced.

CVT Coupled Turbofan Modeling. The CVT turbofan model closely follows the basic simulation. The ability to continuously transition between different gear ratios is characterized by a set of discrete ratio intervals. For each considered gear ratio, the simulation of fixed-gear turbofan is performed, and an interpolation

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Fig. 6 Schematic drawing of a turbofan



Fig. 7 Fixed-gear turbofan simulation flowchart

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Fig. 8 Illustration of CVT coupled turbofan with variable bypass nozzle: (1) fan, (2) CVT gearbox, and (3) variable bypass nozzle

scheme bridges the gaps between the preselected values. While the real CVT will likely exhibit an efficiency dependency on speed and load, the current analysis considers an idealized case, absent of transmission losses. Furthermore, no weight has been assigned to the CVT, and therefore, no thrust-to-weight comparison was conducted. This highlights the cycle ramifications, rather than assessing the performance of a specific CVT design.

CVT Coupled Turbofan Model With Variable Bypass Nozzle. The most advanced configuration, which includes CVT as well as the variable by pass nozzle, is demonstrated in Fig. 8. For the inclusion of a variable bypass nozzle, a gamut of nozzle areas are tested. For each selected area, a wide range of gear ratios and core speeds are examined. At each of these combinations, the thrust and fuel mass flow are logged. In order to acquire minimal fuel consumption for a required thrust, the most efficient operating conditions are defined as a function of gear ratio, nozzle position, and core RPM. The optimal combinations are selected as the engine operating condition.

Model Validation

For the turbojet configuration, the output of the in-house code is compared with the results of the commercial GASTURB 11 software. Following a thorough inspection of each station's temperature and pressure, as well as the system's integral performance parameters (thrust and fuel consumption), a good agreement between GASTURB 11 and the in-house code is seen. Figure 9 presents the operating line computed by both software simulations, where the location of the engine operating line appears consistent. Moreover, calculating the thrust and fuel flow at various RPM lines demonstrates a maximum error of 5.1% (Table 1). Accurately modeling the trends and with reasonable quantitative accuracy, the in-house code is considered to be in close correlation with the commercial software.

In order to further validate the MATLAB code capabilities, the simulation of the fixed-gear turbofan is contrasted against the output of GASTURB 11 simulation. Similarly, with a maximum error of 4.3% for the tested conditions, the correlation between the two models is deemed strong (Table 2).

Results

CVT Coupled Turbofan. With the verification of code integrity for core and bypass streams, the implications of fan gear ratio change on engine performance can be evaluated. Figure 10 depicts the fuel consumption versus thrust variations at a range of gear ratios. The performance lines for different gear ratios are clustered together, where no distinctive trends are noticeable. Since most gear ratios exhibit similar fuel consumption per selected thrust, there exists no advantageous ratio. This would effectively render the CVT useless, and a fixed-gear turbofan, with a correctly selected gear ratio, would be preferred by the designer.



Fig. 9 Turbojet compressor map from GASTURB 11 and in-house simulation

Table 1	Turboie	thrust a	nd fuel	flow at	different	RPMs
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Mechanical RPM		86,800	97,650	108,500
Thrust (N)	GASTURB 11	110	160	220
	MATLAB code	108	155	216
	Error (%)	1.8	3.1	1.8
Fuel flow (g/s)	GASTURB 11	5.32	6.59	8.62
	MATLAB code	5.05	6.3	8.3
	Error (%)	5.1	4.4	3.7
Equivalence ratio	GASTURB 11	0.238	0.254	0.283
	MATLAB code	0.227	0.245	0.279
	Error (%)	4.6	3.5	1.4

Table 2 Turbofan thrust and fuel flow at different RPMs

Mechanical RPM		86,800	97,650	108,500
Thrust (N)	GASTURB 11	198	284	368
	MATLAB code	206	291	380
	Error (%)	4.0	2.5	3.3
Fuel flow (g/s)	GASTURB 11	6.17	7.88	9.89
	MATLAB code	6.37	8.06	10.31
	Error (%)	3.2	2.3	4.3
Equivalence ratio	GASTURB 11	0.21	0.231	0.259
	MATLAB code	0.218	0.238	0.269
	Error (%)	3.8	3.0	3.9

Toward seeking an explanation for this rather unexpected result, the operating lines for each gear ratio are charted on the fan, compressor, and turbine maps (Fig. 11).

A distinct spreading motion is observed on the fan and compressor maps. Meanwhile, the operating lines on the turbine map tend to remain clustered together (Fig. 11(d)) with a gradual drop in efficiency at fan overspeed ratios (Fig. 11(c)). Therefore, as the operating line moves to an advantageous position on a given component map, the benefit is offset by another component moving to an inferior position. This simultaneous shift in operating line position along various component maps is the main reason for not observing a significant fuel consumption response to gear ratio modification.

Therefore, in order for CVT to provide a distinct thrust or fuel consumption improvement, another independent control variable needs to be introduced; this enables an additional setting for the component map location. **Fixed-Gear Turbofan With Variable Bypass Nozzle.** Toward decoupling the fan operation from the core, a variable bypass nozzle is introduced. Compared to the hot gas path, addition of a flow control variable to the cold stream is a much better solution in terms of reduced cost and complexity. Therefore, changing the bypass nozzle area and keeping the core nozzle fixed allow independent control to vary mass flow through the bypass without affecting the core stream. For the nominal gear ratio, Fig. 12 portrays the ramifications of variable bypass area on the performance of each component. As shown in Fig. 12(*a*), the fan operating line can be directly controlled, without influencing the compressor or turbine performance (Figs. 12(b)-12(d)).

Hence, combining the effect of the "fanning" motion caused by the bypass area change with the spreading movement due to gear ratio variation, the engine operating line can be independently positioned to any location on the fan map. Hence, with this added degree of control, component matching problems between fan and core could be greatly reduced, and operating conditions can be better placed to higher thrust and efficiency points.

CVT Coupled Turbofan With Variable Bypass Nozzle. For a representative flight condition (Ma = 0.5 at altitude of 3000 m), CVT coupled turbofan with variable bypass nozzle is simulated for a broad range of gear ratios, nozzle positions, and core RPMs. The produced thrust and required fuel flow are calculated for each of the aforementioned combinations, and those that result in minimal consumption at a given thrust are selected as the engine operating condition. In Fig. 13, the minimum fuel consumption points are charted on the fan component map, resulting in the maximum efficiency operating line. As shown in Fig. 12, the compressor and turbine performance is not affected by the changes in bypass nozzle area and remains unaltered from the prior investigated CVT coupled operation (Fig. 11).

Contrasting the performance of different cycles investigated, Fig. 14 depicts the attainable thrust versus fuel consumption at the same flight condition. The original turbojet, from which all turbofan models were derived, exhibits lowest fuel consumption at low thrust. However, with increasing demand of thrust, the fuel mass flow is rapidly increased. The fixed-gear turbofan extends the attainable thrust range of the engine by 40%. However, the fuel consumption is increased by up to 50% even at lower thrust operating point due to off-design conditions imposed on various components. The addition of variable bypass functionality to the fixed-gear turbofan enables the system to achieve its maximum attainable thrust (65% improvement over turbojet), while providing limited fuel consumption reduction (5% improvement over fixed-gear turbofan).

Finally, extending the analysis to the CVT coupled turbofan with variable bypass, a distinct fuel consumption advantage can be seen over its fixed-gear counterpart. The difference is mostly evident at 70% of its maximum thrust and lower. For example, at 200 N, 150 N, and 100 N, the CVT associated improvement in fuel consumption is 3.5%, 5%, and 7.5%, respectively.

Therefore, it can be concluded that the CVT coupled turbofan with variable bypass is superior to other turbofan designs at any thrust requirement and advantageous to turbojet design at thrust requirement above 130 N.

Feasibility Analysis

Toward confirming the concept's validity, an extensive survey has been carried by examining the current state of the CVT technology and its applications.

The CVT know-how has improved immensely since it was first used in the late 19th century. Many automotive companies now incorporate a CVT in at least some of their designs; most notably is Nissan, which offered a CVT in at least 12 of its designs, past and present [13]. Current CVTs are capable of operating in high-power applications and can be seen in trucks,

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Fig. 10 CVT coupled turbofan—fuel flow versus thrust



Fig. 11 CVT coupled turbofan—operating lines on maps of (a) fan, (b) compressor, (c) turbine efficiency, and (d) turbine mass flow

buses, agricultural vehicles, and power generators of over 250 kW [14]. Furthermore, similar CVT designs can be adapted for high-speed applications such as fan drives and superchargers of over 30,000 RPM. The myriad of uses for the CVT led to the perception that at least some designs may be used to

power the fan of a microgas turbine engine. This idea has not gone unnoticed by major engine manufacturers; Pratt & Whitney Canada registered a 2008 dated patent for the power variability of a gas turbine via continuously variable transmission [15].

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Fig. 12 Turbofan with variable bypass nozzle—operating lines on maps of (a) fan, (b) compressor, (c) turbine efficiency, and (d) turbine mass flow



Fig. 13 Fan map of the CVT coupled turbofan with variable bypass nozzle—maximum efficiency operating line

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Fig. 14 Comparison of various cycles-fuel flow versus thrust

Subsequently, the industrial CVT design solutions are contrasted, which include a variable diameter pulley, a magnetic CVT, a toroidal CVT, and a continuously variable planetary (CVP). Given our required specification of high speed, an in-line shaft design may be more suitable, eliminating the variable diameter pulley design. Although the magnetic CVT is of the in-line shaft configuration, the system is heavier and performs better as a power split device than a power transmission unit. Hence, the remaining design space consists of toroidal CVT and continuously variable planetary gearboxes. Combining the conclusions of the feasibility analysis with the mechanical constraints associated with shaft speed and engine power, it can be suggested that the integration of the CVT is best suited for microgas turbine engines with 150–300 mm cores.

Summary

The study conducted investigates the possibility of converting a micro-turbojet into a variable cycle micro-turbofan with the goal of enhancing the operational performance of the original engine. The proposed method consists of incorporating a CVT to couple between the original turbojet core and a fan. It is necessary to add a variable bypass nozzle to enable utilizing the full potential of the adaptive versatile microengine. Furthermore, the matching of the fan with the core engine is less constrained, since control over the operating line allows for accommodating a wide range of designs.

The performance of the suggested cycle is evaluated by an in-house developed MATLAB code. For the baseline turbojet and turbofan configurations, the model is validated versus well-known industrial simulator. Contrasting the findings with the CVT coupled turbofan with variable bypass nozzle, significant improvement in thrust at reduced fuel consumption is observed. Toward assessing the implementation of this technology into a realistic application, a mechanical feasibility study is conducted by exploring knowledge base of established industry. According to the best of our knowledge and the current state of art, the suggested conversion process can be realistically achieved.

Conclusions

If a continuously variable coupling is introduced between a fan and an existing micro-turbojet engine, the ability to

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change gear ratios while maintaining the core running at its optimum enables operation in a wider gamut of conditions and enhances the performance, all the while maintaining a simple single spool configuration. Moreover, cutting down cost and shortening the design process to a minimum, the conversion entails no changes to the core design. From a logistics standpoint, utilizing an existing micro-turbojet engine provides an extended application range for the same readily available components.

The implications of this enhanced engine technology are especially important for low-cost markets such as microgas turbines. For example, a low thrust turbojet, which could not be prior implemented on an UAV, can now be converted into an adaptive versatile engine with significantly higher thrust. Moreover, the general reduction in fuel consumption directly translates into an increase in range or loiter time. Alternately, for the same range, reducing the weight of fuel on board can make room for additional payload. Another key aspect is the added flexibility of the engine, which enables efficient and optimal operation during takeoff, cruise, and high-speed flight.

Nomenclature

- $A = area (m^2)$
- C_D = discharge coefficient
- C_v = heat capacity at constant volume (J/kg K)
- D = diameter(m)
- h = specific enthalpy (J/kg)
- H =altitude (m)
- $\dot{m} = \text{mass flow (kg/s)}$
- N =rotation speed (RPM)
- P = pressure (Pa)
- $P_l = \text{part load factor (combustor)}$
- $P_{\text{out}} = \text{turbine output power (W)}$
- \dot{Q}_r = specific fuel energy (J/kg)
- R = specific gas constant of air (J/kg K)
- T =temperature (K)
- U =velocity (m/s)
- $Vol = volume (m^3)$
 - γ = heat capacities ratio
 - $\eta = \text{efficiency}$

- $\nu =$ kinematic viscosity (m²/s)
- Π = nondimensional quantity
- $\rho = \text{air density (kg/m^3)}$
- $\Omega = \text{combustor loading parameter (kg/s Pa^{1.8} m^3)}$

Abbreviations

- CVP = continuously variable planetary
- CVT = continuously variable transmission
- LP = low pressure
- RPM = revolutions per minute
- SLS = sea level standard
- TSFC = thrust specific fuel consumption
- UAV = unmanned aerial vehicle

Subscripts

- a = engine inlet condition
- air = air property
- $\operatorname{air}_{\operatorname{core}} = \operatorname{air}$ through the core property
- $air_{fan} = air$ through the fan property
- b, comb = combustor property
 - c = compressor property
 - d = diffuser property
 - dp = design point
 - f =fuel property
 - F =fan property
 - m = mechanical property
 - n = nozzle property s = ideal condition
 - s = sea level condition
 - t =turbine property
 - i = unonne property
 - 0 = stagnation condition 2 = compressor inlet condition
 - 3 = compressor outlet condition
 - 4 = turbine inlet condition
 - 5 = turbine outlet condition

9, e = engine outlet condition ' = fan subsection condition

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