Modeling Turboshaft Engines for the Revolutionary Vertical Lift Technology Project

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ABSTRACT

Turboshaft engine performance and weight models were developed to support conceptual propulsion and vehicle mission design in support of the National Aeronautics and Space Administration's (NASA) Aeronautics Mission Research Directorate's (ARMD) Revolutionary Vertical Lift Technology (RVLT) Project. These models were developed using open data sources, assuming current and advanced technology levels, and range from 650 to 7,500 shaft output horsepower (485 to 5,600 kW). Documenting the methodology, assumptions, and resulting performance realizes important benefits for NASA and the aviation community. NASA concept vehicle efforts using these propulsion models can more readily shared among the government, industry and university community as common baselines to support current and future work. Assessing the benefits of advanced technologies and new configurations can be facilitated using these models, which helps guide technology investment. As the various modeling conceptual vehicle and mission analysis environments advance, these models can be used directly for broader systems analysis studies, including optimization within the propulsion model itself. To perform this effort, the turboshaft engine is briefly discussed, highlighting the specific components and their expected performance characteristics over the power range and technology levels considered. Engine configurations will also be discussed as they will vary based on power output and assumed technology level. Engine performance, such as airflow, power output and weight will be reported, noting trends that are important for system studies. The effect of advanced propulsion technologies on RVLT concept vehicles are also reported. Finally, potential future propulsion modeling work will be proposed.

INTRODUCTION

NASA's Revolutionary Vertical Lift Technology (RVLT) project continues to research and develop technologies to support vertical take-off and landing (VTOL) vehicles. Last year, the RVLT project released a set of vehicle / mission models in References 1 and 2 that are representative of the broad variety of vehicles being proposed to fulfill an exciting vision of future urban air mobility (UAM). Care was taken to develop vehicles and missions that could be used to identify and prioritize research and development (R&D) efforts within the project, but not intentionally endorse or denounce any vehicles or concepts under development. VTOL operations puts unique requirements on propulsion and power systems; therefore models to better define and understand these systems are important considerations in overall vehicle and mission assessment. Although many UAM concepts are conceived as all-battery electric; present shortfalls in battery energy density and electrical infrastructure suggest that turbine-based generator systems may be advantageous to meet near-term energy needs or enhance vehicle capability and operational flexibility requirements. Thermodynamic and weight models were developed for the 650 to 7,500 shaft output horsepower (485 to 5,600 kW) range, representative of today's operational and future planned engines. The models were developed using only open sources to allow the models to be freely discussed and distributed. They are parametric in nature, to allow the user to vary some engine design parameters that will update thermodynamic results for technology assessment and optimization studies; a parallel NASA engine modeling effort is discussed in Reference 3.

Turboshaft engine thermodynamic modeling is discussed first, including methods used, component performance and engine configurations. Engine weight modeling is discussed next, including important factors for the overall design and weight performance. Then overall turbine engine results are discussed, noting how power-to-weight and efficiency vary with size and technology level. Results from the engine thermodynamic and weight modeling are used for a few of the RVLT UAM concepts, to show their effect on overall vehicle size and performance. Future work is then discussed and finally a summary of this effort.

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ENGINE THERMODYNAMIC MODELING

The Brayton (constant-pressure combustion) thermodynamic cycle is used for engine modeling; the block diagram for a simple, single-spool (core) turboshaft with free power turbine is given in Figure 1. Free power turbine indicates it is on its own spool (or shaft) and is free to turn at its own rpm. Major engine parameters include overall pressure ratio (OPR) of the engine, compressor pressure ratio (which determines compression system exit temperature, T3), combustor exit temperature (T4), as well as turbomachinery (compressor and turbine) efficiency. A nozzle pressure ratio of 1.1 (nozzle entrance / ambient total pressure) is assumed; not that the engine produces thrust, but to set the maximum work from the core gas stream and still leave sufficient gas pressure to exhaust from the engine. A more complete discussion about the Brayton cycle and gas turbines can be found in textbooks such as References 4 and 5. The object-oriented analysis framework, the Numerical Propulsion System Simulator (NPSS, References 6 and 7), is used to perform the gas turbine analyses. NPSS contains standard 0/1-D elements for the gas turbine components. These are configured into a representative steady-state, thermodynamic model. Assumptions concerning component performance and specific engine configurations are covered next.

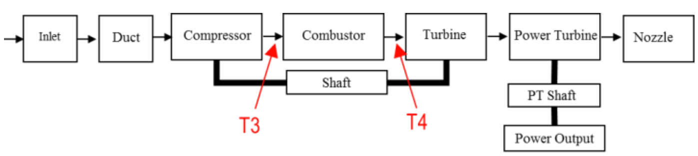


Figure 1. Simple, single-spool turboshaft with free power turbine.

Turbomachinery efficiency and flow

Turbomachinery system efficiency and flow are critical factors in gas turbine performance. For this study, turbomachinery efficiency trends shown in Figure 2 are used. A discussion of their origin and related information is given in Reference 8. Models for current engines use the current technology line; with advanced engines using the advanced technology line. The future line is not used for this study, but is included for completeness. As implemented, the user can set the desired technology levels along a particular level or a given fraction between the different technology levels. Note: for engine modeling, turbomachinery efficiency is set by the lowest corrected flow rate found in a specific component; this is based on exit conditions for each compressor component and entrance for each turbine component. Compressor performance maps for flow, speed, efficiency and stall margin were generated from the computer program reported in Reference 9, based on approximate compressor pressure ratio and compressor type. For turbine performance, performance maps from previous, similar turboshaft engine models are used. All turbomachinery maps are then scaled within NPSS at the engine design point.

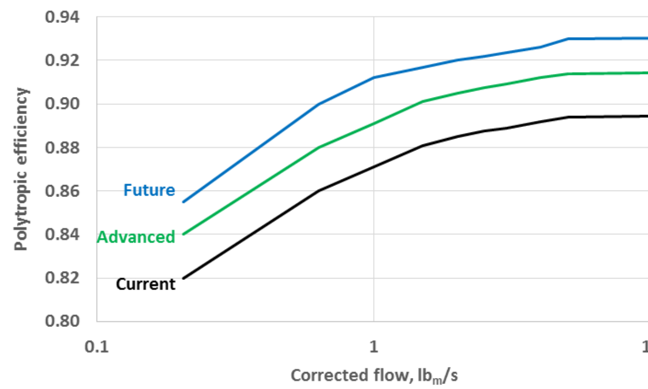


Figure 2. Turbomachinery polytropic efficiency characteristics.

Combustor performance

A fairly simple combustor model is used for all engines, although combustion efficiency and total pressure loss could actually vary with engine size and technology level. A typical hydrocarbon fuel ($C_1H_{1.94}$) with a lower heating value of 18,400 BTU/lb. (42.8 MJ/kg) and 99.9% combustion efficiency is used. A constant 5% total pressure loss is assumed across the combustor. No combustor cooling airflow is assumed, which for these simple models would only been seen in a reduced T4. Emissions for oxides of nitrogen are not considered in this effort, although it would be simple to add to the models, as was reported in Reference 8.

Turbine cooling

Turbine cooling is another important factor in engine performance; setting engine and flowpath complexity and material choices that factor into weight. The methods discussed by Gauntner in Reference 10 are used to estimate cooling airflow rates. As technology advances, less cooling airflow would theoretically be needed (all other factors being constant). However, more advanced engines tend to have higher OPR, resulting in smaller corrected flows in the high pressure turbine section where the bulk of turbine cooling airflow is used. At smaller corrected flow rates, the turbine material surface area per flow actually increases – suggesting that cooling airflow should actually increase as a fraction of turbine airflow. Without definitive information to vary turbine cooling flowrate factors, they are maintained across the various engine models (except as noted later). Turbine cooling parameters can easily be updated to model the effects of higher temperature-capable turbine materials, thermal barrier coatings or more effective cooling technologies.

ENGINE CONFIGURATIONS

Engine configuration includes a variety of factors: number of spools (shafts), whether turbomachinery components use axial or centrifugal / radial flow; and for multiple spools for the core, the split of compression work done on the compressors on each spool. Engine configurations are delineated based on engine power class.

Small: 650 hp class

For the smallest power class, engine simplicity and therefore cost are important and those engines are represented by the block diagram shown in Figure 1. Looking at some of the older engines in this power class, the compressor tended to be an axial-centrifugal design to achieve desired engine OPR and efficiency. Reference 11 discusses centrifugal compressor research performed under the small gas turbine engine technology program to enable current single centrifugal stage designs. These single centrifugal stages can achieve the pressure ratio of older, axial-centrifugal at reasonable efficiency levels. The engine configuration then becomes a single centrifugal stage combined with a combustor and a single, axial stage each for the core turbine and the free power turbine. To further reduce weight, titanium instead of steel can be used for the centrifugal compressor and other components. For the advanced version, achieving significantly higher compressor pressure ratio (and therefore potentially higher fuel efficiency) would be difficult within the single centrifugal stage and adding axial stages would compromise simplicity. There are additional considerations going from centrifugal to axial-centrifugal on the same shaft, but that will not be discussed here. The advanced version only includes a slight improvement in turbomachinery efficiency (from current to advanced technology) and minor updates in turbine materials to further reduce weight.

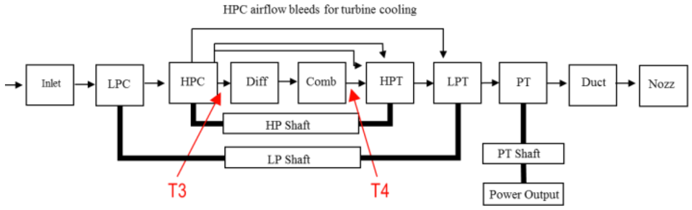
Mid: 2,000 to 3,000 hp class

For the mid power class, additional complexity is warranted for the accompanying improvement in fuel efficiency. References 12 and 13 give engine configuration and performance for the T700 engine; which is used to develop the current technology engine at 2,000 hp. Similar to the small power class, its configuration is represented by the block diagram in Figure 1. However, the actual compressor design is axial-centrifugal with OPR≈18. For the engine model, the axial and centrifugal portions are modeled separately. The core turbine is two stages as well as the free power turbine to meet expected efficiency levels. The advanced engine is representative of potential products from the Advanced Affordable Turbine Engine (AATE) demonstrator program; overall goals are found in Reference 14. The advanced engine could be single spool or two spool for its core. References 15 and 16 are white papers from competing company sites discussing the various reasons for choosing either configuration. Considering the fact that the Improved Turbine Engine Program awarded General Electric Aviation to further develop its T901 engine design, a similar configuration was chosen for this work. Turbomachinery efficiency levels were chosen at the advanced level, with some minor additional pressure ratio assumed for both the axial and centrifugal portions of the compressor versus the current engine and an additional free power turbine stage to maintain efficiency at such high energy extraction per airflow.

Large: 5,000 to 7,500 hp class

The large power class includes similar engine configurations as the mid-power class represented in Figure 1, although the compressor for some engines is all axial. One example of an all-axial engine is the Rolls-Royce T406, used for the V-22; similarly, axial-centrifugal designs can also be found. The current engine is modeled as axial-centrifugal compression and is assumed to be similar to the T55. Engine characteristics for modeling are from References 12 and 17. Current technology levels for turbomachinery efficiency are assumed; T4 and turbine cooling airflow are varied to match stated airflow, power and fuel consumption levels. Reference 14 also discusses the Army’s Future Affordable Turbine Engine (FATE) program; which supports advanced engine demonstrators in this class and is used to set performance goals for the advanced engine. A notional version of the GE38/T408 (mid technology engine between many current engines and FATE goals in fuel efficiency) was also modeled. Various characteristics were compiled from References 12, 18 and 19. Reference 18 is an engine brochure for the T408; which relates its performance to improvements versus the T64. Reference 19 is an engine brochure for the T64. Advanced technology levels for turbomachinery efficiency are assumed, varying OPR and T4 to match compiled characteristics for the T408.

The advanced engine was assumed to meet the FATE engine improvement goals, using the T55 as the base cycle. The assumed engine configuration is shown in Figure 3. A two-spool core is assumed to enable the higher engine OPR to meet fuel efficiency targets. Reference 20 discusses some of the reasons for choosing a two- spool core engine configuration. Advanced technology is assumed for turbomachinery efficiency, with compression work split 30% on the low spool and 70% on the high spool, as discussed in References 8. Splitting the compression work between two spools not only enables higher engine OPR, but can reduce the number of turbomachinery stages in the core. The low pressure spool compressor is assumed all axial, while the high spool is axial-centrifugal. The engine is sized at 7,500 horsepower output.



LPC – low pressure compressor, HPC – high pressure compressor, Diff – diffuser, Comb – Combustor, HPT – high pressure turbine, LPT – low pressure turbine, PT – power turbine, Nozz – nozzle, HP – high pressure, LP – low pressure, PT – Power turbine,

Figure 3. Three-spool (two-spool core) turboshaft with free power turbine.

ENGINE FLOWPATH AND WEIGHT ESTIMATION

Following the engine thermodynamic model development, engine weights and flowpath dimensions are developed. The NASA software tool, WATE++ (Weight Analysis of Turbine Engines, Reference 21), is used to create engine architectures that could achieve the engine thermodynamic cycles produced by the NPSS models detailed in the previous sections. The cycle data required for WATE++ execution, such as air mass flow, temperatures, pressures, pressure ratios, etc., are derived from the engine thermodynamic model output. Both the aerodynamic design point (maximum rated power, sea level static) and off-design cases are used to encompass the maximum performance level (i.e., temperature and pressure) required to size each engine component. The cycle data, the material properties, and design rules for geometric, stress, and turbomachinery stage-loading limits are used to determine an acceptable engine flowpath. Representative engine flowpaths for each of the power class engines are shown in Figure 4.

AM355 stainless steel is used for the compressor components for current technology engines, except the small, 650 hp class engine. For the advanced engines, a titanium alloy is used to significantly reduce compressor and overall engine weight. The small, 650 hp class engines are modeled after the Arrius 2B1 engine that is found in Reference 12. Titanium is used for the current engine instead of stainless steel to reflect the current material trend in small turboshaft engines; Arrius 2B1 has a titanium compressor. Nickel-based alloys are used for the turbine components for all the engines. The nickel-based alloys have a higher density and are heavier, but are required to withstand the high-temperature turbine environment.

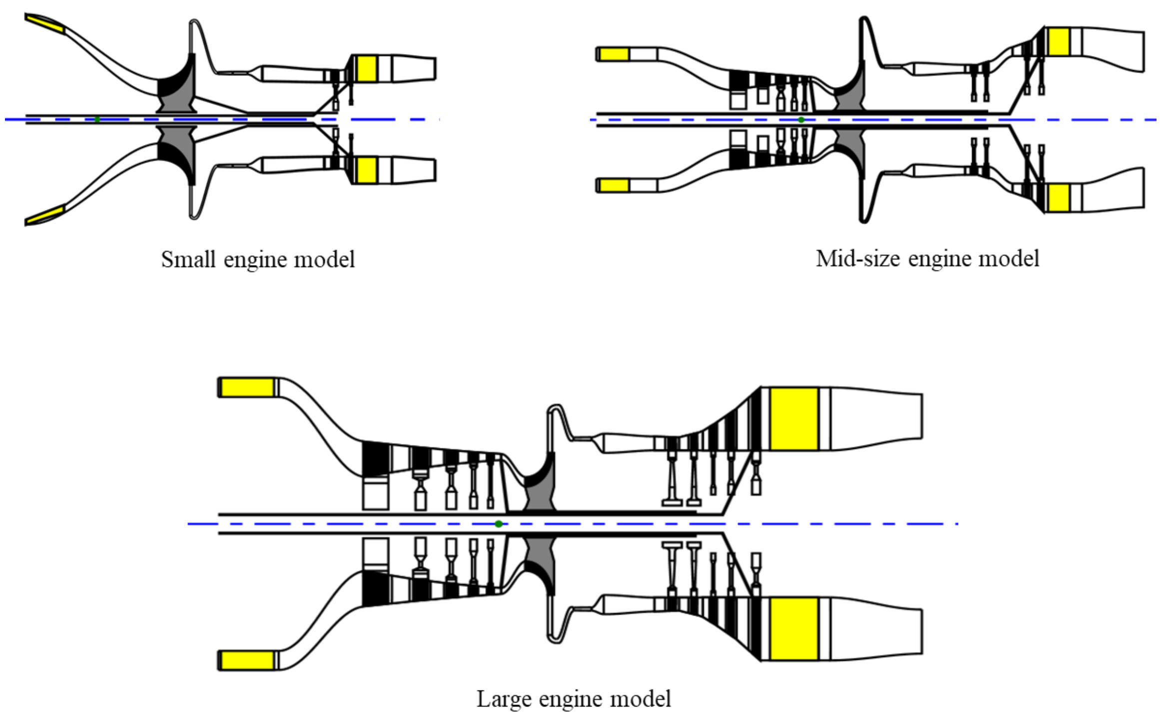


Figure 4. Representative flowpath model for each power class engine.

GAS TURBINE ENGINE OVERALL RESULTS

Table 1 is a summary of the engine size and performance parameters for the various engines modeled as part of this effort. Figure 5 shows power to weight and power specific fuel consumption (PSFC) for various, current gas turbine engines as well as the mid technology, T408 and the advanced, concept engines. Data for current engines were gathered from References 12, 13 and 17-19. Trend lines have been added that could be useful for system studies. Advanced technology results in some impressive improvements in power-to-weight and PSFC reductions, although the improvements are more significant for the mid and large engine power classes. For the small, 650 hp class engines, both are already at high technology levels. The T408 is an interesting data point for the graphs in Figure 5, as its power-to-weight follows the current trend line, but falls between current and advanced engines for PSFC.

Table 1. Engine size and performance parameters

Maximum rated hp, Sea level, ISA	650	660	1,895	3,000	4,916	7,248	7,500
Technology	Current	Advanced	Current	Advanced	Current	Mid	Advanced
Power specific fuel consumption, PSFC, lb/hr/hp	0.526	0.485	0.476	0.360	0.494	0.394	0.330
Airflow, lb/s	4.8	4.1	11.8	14.6	28.1	35.7	28.1
OPR	9	9	17.7	25.2	9.3	20	30
Compressor layout (A=axial, C=centrifugal)	1C	1C	5A + 1C	6A + 1C	7A + 1C	5A + 1C	4A / 3A + 1C
Turbine stages	1 + 1	1 + 1	2 + 2	2 + 3	2 + 2	2 + 3	1 + 1 + 3
Diameter in	16	16	17	16.4	24	27	25
Length, in	28	28	45	47	46.5	58	59
Weight, lb	238	229	458	457	830	1085	750
Power/weight, hp/lb	2.7	2.9	4.1	6.6	5.9	6.7	10

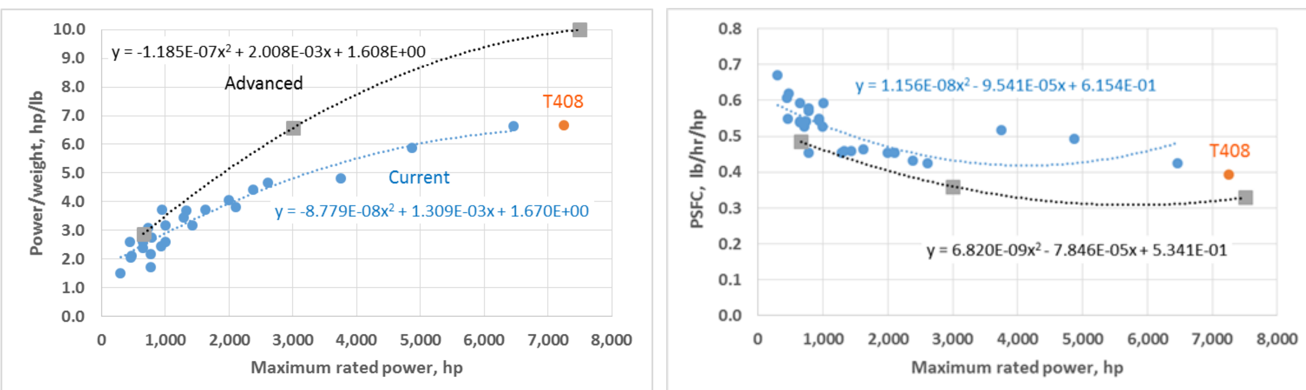


Figure 5. Engine power to weight and PSFC versus horsepower.

MISSION MODELING FOR VARIOUS ENGINE TECHNOLOGY CLASSES

To illustrate the benefits of advanced cycles over current cycles, a small parametric vehicle / mission analysis was performed. The RVLT-developed tiltwing and lift+cruise concept vehicles for UAM research were used and are shown in Figure 6, see References 1 and 2. The tiltwing can carry fifteen passengers (3,000-lb payload), for eight by 50 nautical mile legs plus reserves. The lift+cruise concept is representative of many concepts being proposed; assuming six passengers (1,200-lb payload) and a two by 37.5 nautical mile legs, plus reserves. It uses several rotors for vertical operations, which are stopped while the vehicle uses its wing and pusher propeller similar to a traditional, fixed-wing airplane for climb, cruise, and start of descent. The NASA Design and Analysis of Rotorcraft (NDARC, Reference 22) models are used, assuming the turbo-electric propulsion versions of the vehicles and updating the turbine engine model parameters based on the result of this work. Payload and range were maintained, but design gross weight was varied to achieve a closed design. Table 2 gives selected vehicle characteristics from these analyses. Advanced turbine engine technology can achieve 10-14% reduction in design gross weight, 30-37% reduction in engine weight and 25-40% reduction in fuel usage.

Figure 6. RVLT UAM Tiltwing and Lift+cruise concept vehicles.

Table 2. Selected vehicle / mission results for varying turbine engine technology.

Vehicle	Tiltwing		Lift+cruise	
Engine Technology	Current	Advanced	Current	Advanced
Design Gross Weight, lb	15,470	13,350	6,650	5,970
Engine power, hp	5,190	4,570	1,220	1,220
Engine weight, lb	900	570	370	260
PSFC, hp/(lb/h)	0.380	0.325	0.597	0.360
Fuel, lb	2,500	1,910	295	170

FUTURE WORK

Some additional refinement is planned for model uniformity and to make them easier to modify or update. After release approval, the models and documentation will be available with the NDARC program and its vehicle and mission models. Additional engine sizes might be generated to further refine the power-to-weight and power-specific fuel consumption trend lines. Focus will then shift to the overall turboelectric propulsion and power modeling. Reference 23 reports on work that has already started on methods and modeling tools for more and all-electric systems. These gas turbine models are a necessary part in the overall propulsion and power system assessment being performed under the RVLT project.

SUMMARY

Turboshaft engine performance and weight models were developed using open data sources to support conceptual propulsion and vehicle mission design and performance under the Revolutionary Vertical Lift Technology (RVLT) Project. These models range from 650 to 7,500 shaft output horsepower (485 to 5,600 kW), assuming current and advanced technology levels. Turbine engine methodology, assumptions, and resulting thermodynamic and size / weight performance were presented, as well as a simple propulsion performance assessment using the RVLT urban air mobility (UAM) tiltwing and lift+cruise reference vehicles. Advanced gas turbine engine technology can realize significant improvements in engine power-to-weight and fuel efficiency. Improved engine performance results in significant reductions in vehicle design gross weight, engine weight and fuel usage. Planned future dissemination of the engine models and propulsion modeling work were also discussed.

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