EXO-SKELETAL ENGINE—NOVEL ENGINE CONCEPT

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ABSTRACT

The exoskeletal engine concept represents a new radical engine technology with the potential to substantially revolutionize engine design. It is an all-composite drum-rotor engine in which conventionally heavy shafts and discs are eliminated and are replaced by rotating casings that support the blades in spanwise compression. Thus the rotating blades are in compression rather than tension. The resulting open channel at the engine centerline has immense potential for jet noise reduction and can also accommodate an inner combined-cycle thruster such as a ramjet. The exoskeletal engine is described in some detail with respect to geometry, components, and potential benefits. Initial evaluations and results for drum rotors, bearings, and weights are summarized. Component configuration, assembly plan, and potential fabrication processes are also identified. A finite element model of the assembled engine and its major components is described. Preliminary results obtained thus far show at least a 30-percent reduction of engine weight and about a 10-dB noise reduction, compared with a baseline conventional high-bypass-ratio engine. Potential benefits in all aspects of this engine technology are identified and tabulated. Quantitative assessments of potential benefits are in progress.

KEY WORDS: High Temperature Composite Materials/Structures, Hybrid Materials/Structures, Manufacturing/Fabrication/Processing

INTRODUCTION

Current gas turbine engines are constructed mostly from heavy metals, have central shafts and discs, require lubricated bearings, need extensive cooling for hot components, are subject to catastrophic failure due to disc bursts from high tensile loads, require heavy containment devices, are subject to severe imbalance (or vibrations) that could wipe out the whole rotor stage, are prone to high- and low-cycle fatigue, and are limited for specific vehicle class. A novel engine concept is needed to enable a much lighter engine with capabilities such as: (1) much higher efficiency; (2) improved reliability and risk compared with present technology; (3) flexibility for increased thrust growth; and (4) versatility to power different types of vehicles with radically different power requirements. The objective of this report is to describe that novel type of engine—the exoskeletal engine (ESE), which is of the drum-rotor type. It is an all-composite engine that consists of four concentric shells (or five for counter rotating stages), each made from a different type of composite (polymer, metallic, or ceramic) to accommodate different temperature regimes. The ESE concept subjects all rotating parts to compression, permitting use of notch-sensitive materials (such as homogeneous ceramics) that can operate at much higher temperatures in hot sections of the engine than present materials. It substantially reduces the cooling requirements or allows an engine to operate at much higher temperatures with the same cooling method. It reduces the rolling-bearing stress by permitting multiple rows of bearings, thereby minimizing or even eliminating lubrication and cooling. The ESE allows for progressive engine thrust growth capacity as well as reduces engine size. It is equally applicable to subsonic, supersonic, and hypersonic engines (1). The ESE permits adaptation of turbine-based combined-cycle engines. Some quantitative and qualitative benefits include: elimination of bore stresses, increased bearing life, increased tip speed, reduced airfoil thickness, increased flutter boundaries, elimination of containment requirements, increased blade high-cycle fatigue life, reduced parts count, decreased maintenance cost, decreased sealing and cooling requirements, and reduced blade-tip and case wear. Preliminary results show that the stresses in the blades, bearings, and back-up shell are well below those that are allowable for the composites to be used for these components. A unitized component fabrication is identified, and an initial assembly model is described. A finite element model of the entire engine has been developed indicating at least 30-percent weight savings resulting in a high-thrust-to-weight propulsion system. A video has been made to demonstrate ESE virtual operation. It is noted that, to the authors' knowledge (literature and patent searches) no comparable concept has been published or invented as of this writing.

FUNDAMENTAL CONCEPT

The ESE concept eliminates the central heavy discs and shaft that are in conventional gas turbine engines (Figure 1). Instead, the ESE utilizes a drum rotor with the blades hanging inward from the outside. The concept has three main features: (1) a drum-rotor configuration that subjects all rotating parts to compressive stress fields, (2) an all-composite engine for light weight and for higher ratios of strength and stiffness to density, and (3) unitized components and subassemblies to reduce the part count. The drum-rotor configuration consists of four concentric composite shells: (1) an inner composite shell, which is static and provides for flow path through the center cavity; (2) a stator shell, which is static and supports the guide vanes, (3) a drum-rotor shell, which rotates and supports all blades, and (4) an outer or backbone shell, which supports the bearings and is designed with acceptable hoop stresses to constrain the drum-rotor shell to specified or no radial growth. The unitized component subassemblies include the inlet, the fan stage, the low-pressure compressor stages, the high-pressure compressor stages, the high-pressure turbine stages, the low-pressure turbine stages, and the exhaust. A longitudinal section of the assembled ESE is shown in Figure 2. A longitudinal section of the inner shell is shown in Figure 3; of the stator shell, in Figure 4; of the drum-rotor shell, in Figure 5; and of the exterior or backbone shell, in Figure 6.

A low-pressure turbine is included in Figure 2 in case a two-spool arrangement is needed, which may be the case in order to accommodate improved efficiency operations at off-design points. It is also noted that the combustor is assumed to be the same as that of a conventional high-bypass-ratio engine. Some high-temperature composites may be used in the combustor as the detail design matures. It is also envisioned that a gearbox may be required, which will become evident during detail design of the ESE. The ESE is amenable to several alternative configurations. Those configurations have not gone through preliminary evaluations as yet and are planned to be discussed in forthcoming reports. Limitations of the ESE concept are identified in descriptions of the specific features. It is noted at this point that fabrication of the ESE is by far the major challenge.

INITIAL EVALUATIONS

Projected benefits were based on preliminary evaluations of the areas of concern (weight, cycle, noise, etc.). An Advanced Subsonic Technology (AST) engine was used as the baseline for these initial evaluations. A schematic of the AST engine is shown in Figure 7. The evaluations were performed by using an integrated multidisciplinary computer code identified as Engine Structures Technology Benefits Estimator (EST/BEST). A block diagram of that computer code is shown in Figure 8. The computer code is described in detail (2). Initial component information from the AST engine used for each evaluation is summarized in Table 1. Initial weight benefits obtained from the evaluation are shown in Figure 9 as percentages in weight reduction from the baseline. In addition to weight evaluations, engine thermodynamic cycle evaluations were performed. Results from those evaluations are summarized in Table 2. Comparable results were obtained for smaller thrust engines (3). Initial evaluations for noise reduction of the ESE concept were also performed (3). It is also noted that the thermodynamic performance of the ESE is similar to the baseline engine, and the results show that there are no show stoppers. The results of the noise evaluation are shown in Figure 10. As can be observed there is a potential for about a 10-dB noise reduction. This reduction is due to an inverted exhaust velocity profile, which results from the free-stream flow through the center cavity in the ESE.

BEARINGS

Bearings are a major engineering challenge for realization of the ESE concept. An example of a possible bearing arrangement for the fan stage is shown in Figure 11. Though several bearing concepts, including lightweight ceramic and magnetic bearings, have been proposed (4), herein we only discuss ball bearings made from graphite-carbon composite. The reason for considering ball bearings from graphite-carbon fiber composites is their self lubricating features and high heat conductivity. These properties have the potential of eliminating all plumbing and lubricants that require expensive operations and maintenance. A preliminary assessment of the loads on the ball bearings (the loads transmitted to the backbone shell from the rotor shell) is summarized in Table 3. It is observed that bearing loads are relatively small and easily accommodated. These load values were obtained by assuming that the entire radial load from the rotating shell is transferred through the bearings to the outer backbone shell so that the rotating shell can be kept at zero or near-zero radial growth (Figure 11). As can be seen in Table 3, the average bearing load is 50KN (11.4 kips) per circumferential inch. A multiple row of ball bearings is envisioned as shown in Figure 12 for the radial bearings and in Figure 13 for the thrust bearings. It is evident that a number of rows can be selected to reduce the load per bearing as needed. It is also evident that the rotating shell may need to be configured so that the multiple bearing rows are uniformly loaded. Both of these are challenges that need to be overcome (or accounted for) in the detail design of the ESE. It is noted that the state-of-the-art for conventional bearings is a DN (rotor diameter in millimeters times revolutions per minute) of 2.5 million compared to about 9 million for the ESE. Therefore, developing working bearing concepts for the ESE constitutes a major challenge.

FINITE ELEMENT MODELING

A finite element model of the entire ESE was initiated in order to identify potential fabrication arrangements and to evaluate (1) the integrated behavior of the engine, (2) the internal loads on the components induced by the entire engine, (3) the load transferred from the vehicle to the engine during flight, and (4) engine induced loads on the pylon. The finite element model generated thus far includes all the structural elements. A computer plot of the three-dimensional model is shown in Figure 14.

The estimated weight from the finite element model of the entire engine is about 49KN (11,000 lb) (Table 4) compared to the AST engine of about 98KN (22,000 lb) (Figure 7). Adding about 17KN (4,000 lb) of other parts that are not included in the finite element evaluation results in an ESE weight of about 67KN (15,000 lb), or a weight reduction of about 32KN (7,000 lb), which is about a 30-percent weight reduction in the engine. The large weight reduction will lead to a higher thrust-to-weight propulsion system and improved fuel-burned consumption. The finite element results show that the shell sizes listed in Table 4 are sufficient to withstand steady state anticipated loads. The shells are currently being evaluated for dynamic loads.

A video was developed from the finite element model to illustrate that rotating and static components do not interfere with each other. In addition, the model is presently used to evaluate structural responses such as frequencies, buckling loads, blade and vane stresses, bearing loads, individual shell deformations, and foreign object damage (FOD).

POTENTIAL FABRICATION PLAN

Based on the finite element model and individual (unitized) component simulation, a potential fabrication and assembly concept was identified. A schematic of that concept is shown in Figure 15. All the ESE components are displayed in this schematic except the combustor, which is assumed to be the same as that used for the AST baseline as mentioned previously, and perhaps the only noncomposite component. At this time, it is envisioned that the unitized components can be fabricated by a preform process. In that process, the components are woven to near-final shape first then infiltrated by a matrix that is suitable for expected component temperatures. The authors consider the fabrication of an all-composite ESE (made from polymer, metallic, and ceramic composites) to be a major challenge in its successful evolution from a concept to a marketable product. The fabrication and assembly schematic shown in Figure 15 was used to make a rapid prototyping model, a CAD model of which is shown in Figure 16.

POTENTIAL BENEFITS

Based on the preliminary results, the ESE concept can potentially lead to a large weight savings because the heavy discs and shafts are eliminated, resulting in a higher thrust-to-weight propulsion system. It also leaves a cavity in centerline that could be exploited in several different ways. In subsonic applications, venting the center cavity with a free-stream flow could potentially contribute to a large noise reduction in combination with an inverted exhaust velocity profile. In supersonic-hypersonic applications, the centerline cavity might be used to conveniently house a ramjet or scramjet (or other advanced devices such as a pulse-detonation engine) as part of a turbine-based combined-cycle engine. Such an arrangement could reduce the overall length of the propulsion system and thereby reduce weight and drag significantly.

These benefits and numerous others are listed in Table 5. This list was compiled based on the authors' accumulated aeropropulsion experience and potentially impact of all aspects of engine technology from design, to fabrication, to operation, and to maintenance. Most of the benefits are qualitative and still need to be quantified. Although technical challenges need to be overcome, the authors believe these benefits can be achieved as ESE technology evolves to maturity. The potential benefits and early progress made were incorporated into a patent application. The patent was issued in May 2002 (see Figure 17).

CONCLUSIONS

The revolutionary structural concept of the exoskeletal engine (ESE) was described in some detail. Initial evaluation results for geometry configuration, bearings, unitized fabrication, and assembly were presented. An assembled-engine finite element model was described, and weights of components and the engine obtained therefrom were summarized. A rapid prototype model and projected qualitative benefits were also discussed. Collectively, the progress made to date indicates that ESEs are viable with substantial benefits in all aspects of engine technology.

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Table 1.—Component Information for Advanced Subsonic Technology Engine.
[Fan tip speed is 1100 ft/sec; fan bearing rotor diameter in mm × rpm is 6 million.]

Initial engine parameters	Engine components					
	Fan stage	Low-pressure compressor	High-pressure compressor	High-pressure turbine	Low-pressure turbine	Comments
Number of stages	1	3	10	2	5	
Weight flow, lb/sec	1442	156	74.4	53.5 11.2[a]	67.1	Sea level
Inlet tip radius, in.	68.5	25.3	15.4	15.6	17.3	
Hub/tip ratio	0.35	0.8	0.78	0.92	0.88	
Pressure ratio	1.3	2.4	25.9	5.42	11.6	
Rotational speed, rpm	1833	7333	10 417	10 417	7333	

[a]From cooling. (1 lb/sec = 4.45N/sec; 1 in = 2.54/cm)

Table 2.—Exoskeletal Engine Characterization.

	Sea level static	Maximum climb	Cruise
Corrected flow, lb/sec	2800	3115	2854
Corrected speed, rpm	2547	2750	2445
Fan pressure ratio	1.50	1.54	1.414
Fan efficiency	0.89	0.89	0.92
Fan tip diameter, in.	135	----	----
Fan tip speed, ft/sec	1500	1620	1440
Fan hub/tip ratio	0.4	----	----
Compressor pressure ratio	26.15	29.64	22.4
Compressor efficiency	0.88	0.82	0.89
Compressor tip diameter, in.	97	----	----
Compressor tip speed, ft/sec	1010	1087	981
Compressor hub/tip ratio	0.95	----	----
High-pressure turbine pressure ratio	5.20	5.20	5.25
High-pressure turbine efficiency	0.94	0.94	0.94
Low-pressure turbine pressure ratio	4.3	4.48	4.5
Low-pressure turbine efficiency	0.94	0.94	0.94
Bypass ratio	8.5	8.59	10.6
Turbine inlet temperature, °R	3045	2900	2478
Thrust, lb	70 000	16 527	10 890
Specific fuel consumption, lb/lb/hr	0.31	0.547	0.511

(1 lb/sec = 4.45N/sec; 1 in = 2.54 cm; 1 ft/sec = 76.2 cm/sec; 1 lb = 4.45N)

Table 3.—Initial Ball-Bearing Loads for Exoskeletal Engine (Subsonic).

Rotation speed, rpm	1835
Outer radius, in.	68.2
Inner radius, in.	24.8
Number of blades	31
Material	Titanium
Bearing load, kips/blade	159
Blade weight, lb/blade	31
Bearing circumferential load, kips/circumferential inch	11.4

(1 kip = 4.45KN)

Table 4.—Exoskeletal Engine Weights Summary Obtained From Finite Element Model.

(1 lb = 4.45N)

Shell name	Dimensions, in.	Nodes	Elements	Blades				Thickness, in.	Weight, lb
				Type[a]	Stage	Number	Thickness, in.		
Inner composite shell	Length: 234.46 Diameter 1: 47.5 Diameter 2: 39.5	372	384	----	----	----	----	0.25	410
Stationary composite shell	Length: 277.24 Diameter 1: 51.9 Diameter 2: 39.5	31 632	23 823	HPC	10	1261	0.25	0.5	1844
				LPC	3	215	.25		
				HPT	2	244	.25		
				LPT	5	771	.25		
				Vane	1	16	.5		
Rotating composite shell	Length: 195.45 Diameter 1: 120.94 Diameter 2: 74.3	30 283	22 554	HPC	10	1261	0.125	0.5	2530
				LPC	3	215	.125		
				HPT	2	244	.125		
				LPT	5	771	.125		
				Vane	1	16	.5		
Outer composite shell	Length: 280.7 Diameter 1: 149 Diameter 2: 89	2952	2920	----	----	----	----	0.5	5855
Combined shell engine assembly	Max. length: 312 Max. diameter: 149 Min. diameter: 39 5	65 239	49 681	----	----	----	----	----	10 639

[a] HPC is high-pressure compressor; LPC, low-pressure compressor; HPT, high-pressure turbine; and LPT, low-pressure turbine.

Table 5.—Exoskeletal All-Composite Engine Projected Benefits.

- Eliminate disk and bore stresses
- Utilize low-stress bearings
- Increase rotor speed
- Reduce airfoil thickness
- Increase flutter boundaries
- Minimize/eliminate containment requirements
- Increase high mass flow rate
- Reduce weight by 50 percent
- Decrease turbine temperature for same thrust
- Decrease emissions
- Provide higher thrust-to-weight ratio
- Improve specific fuel consumption
- Increase blade low-cycle and high-cycle fatigue lives
- Reduce engine diameter
- Reduce parts count
- Decrease maintenance cost
- Minimize/eliminate sealing and cooling requirements
- Minimize/eliminate blade-flow losses, blade and case wear
- Free core for combined turboram jet cycles
- Reduce noise
- Expedite aircraft/engine integration
- Minimize/eliminate notch-sensitive material issues

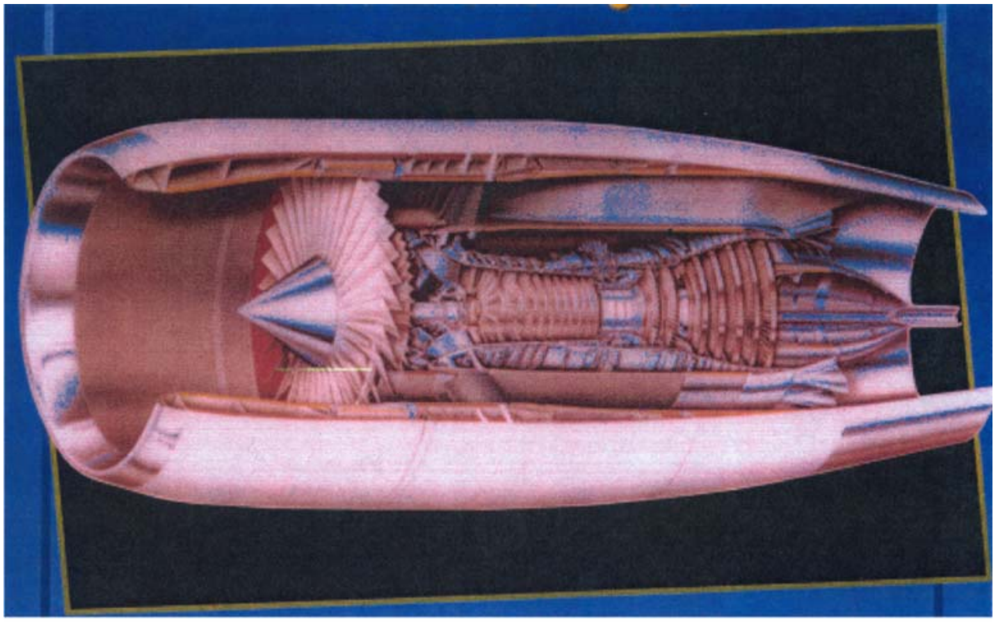


Figure 1.—Conventional high-bypass-ratio gas turbine engine.

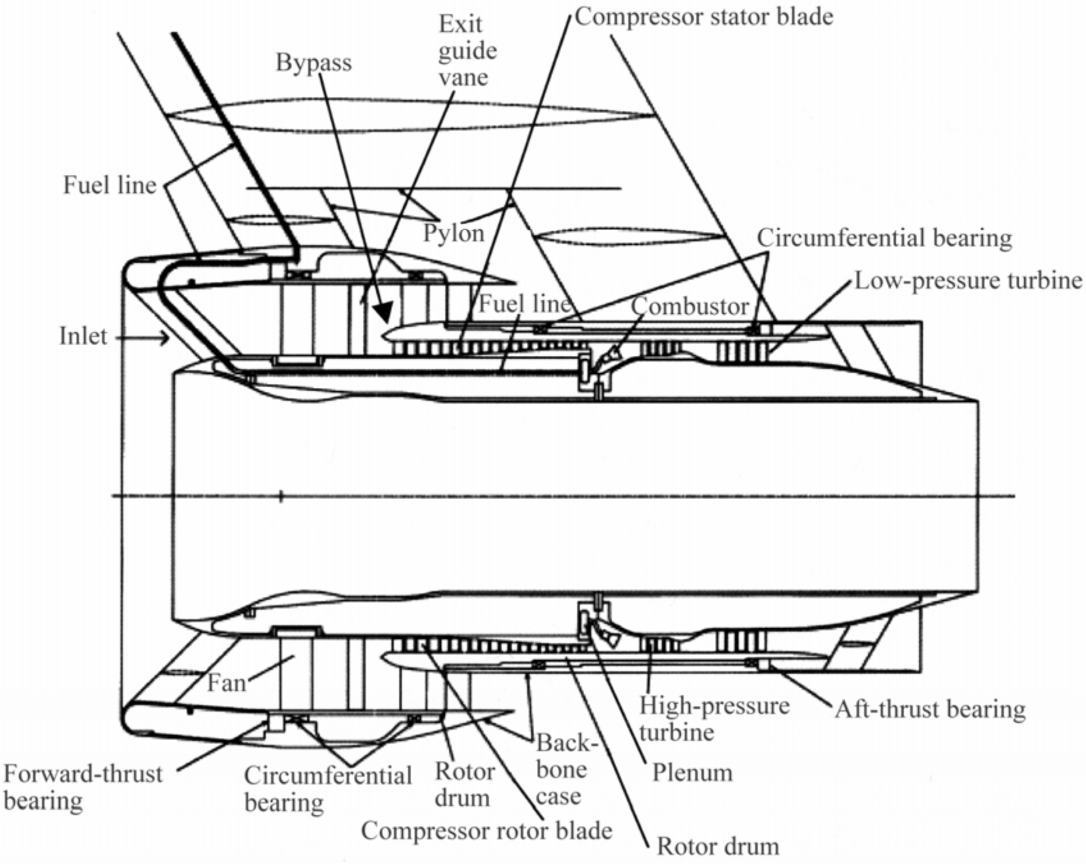


Figure 2.—Longitudinal section of assembled exoskeletal engine.

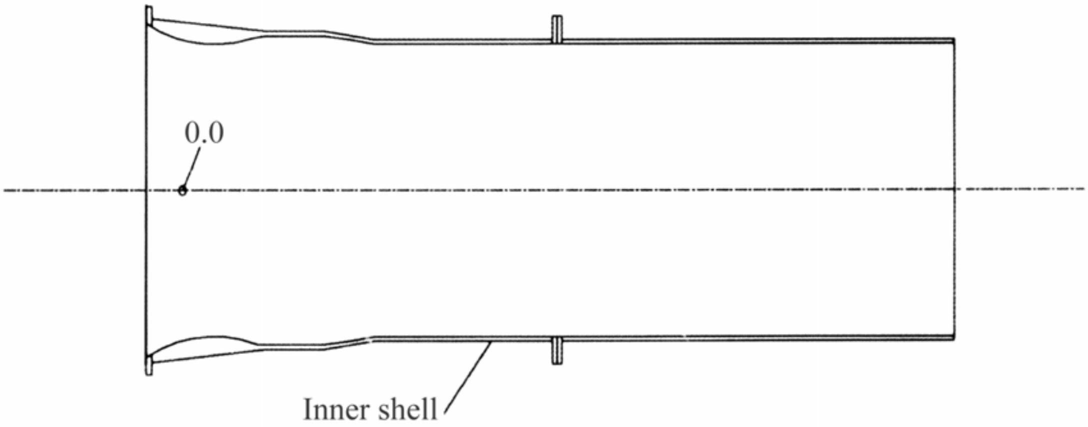


Figure 3.—Longitudinal section of exoskeletal engine inner shell.

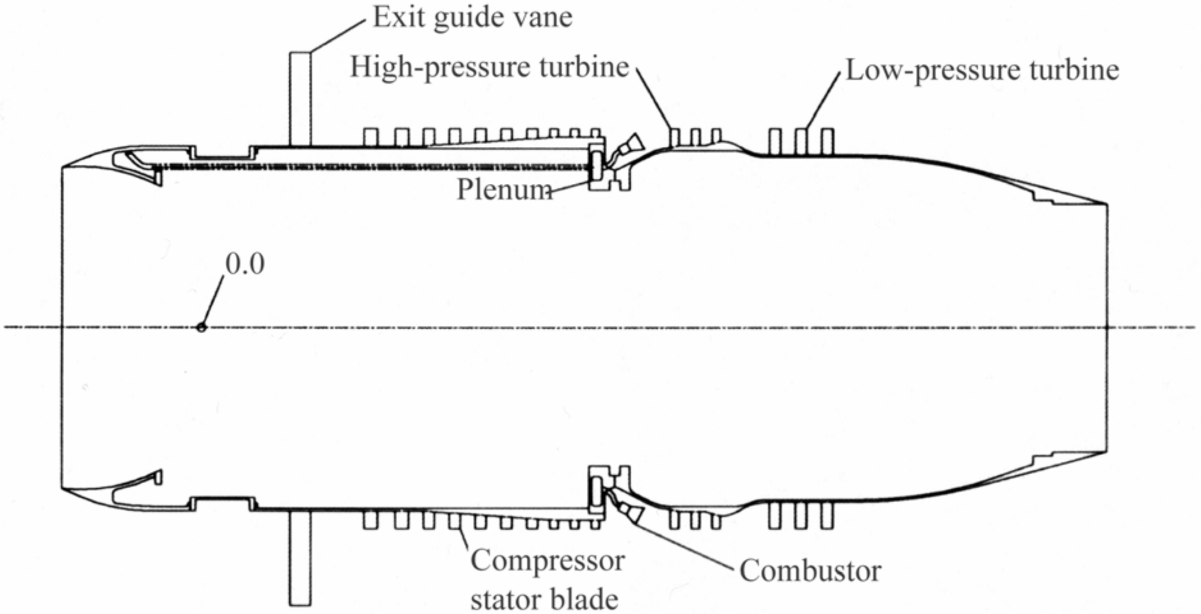


Figure 4.—Longitudinal section of exoskeletal engine stator shell.

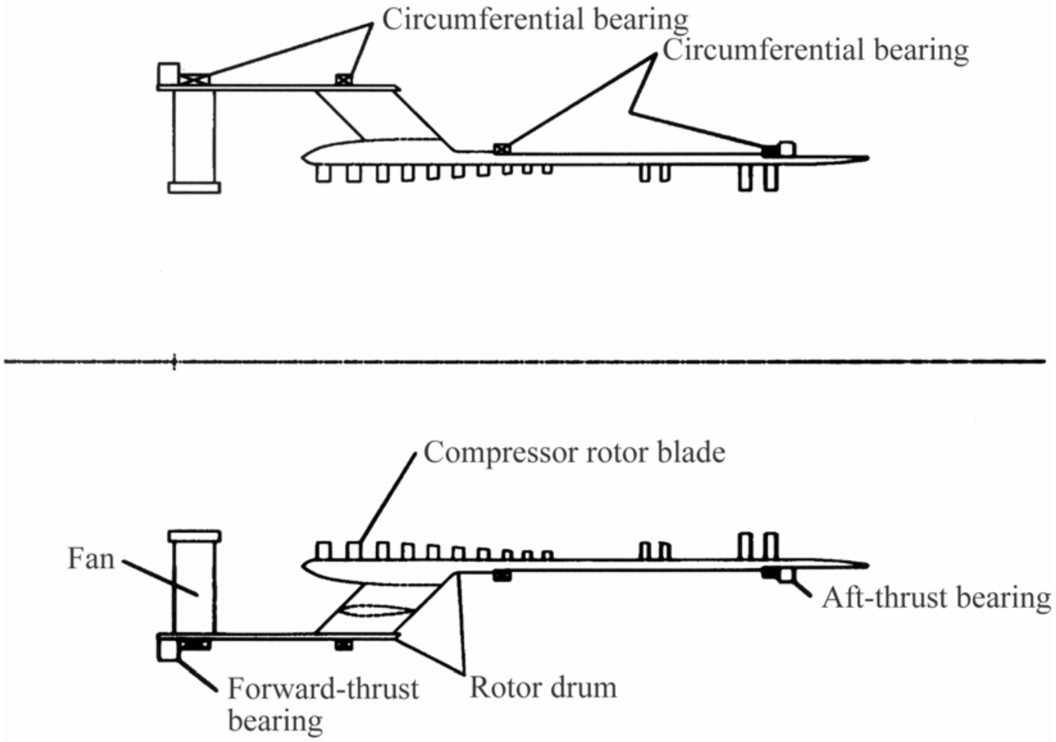


Figure 5.—Longitudinal section of exoskeletal engine rotor (drum-rotor) shell.

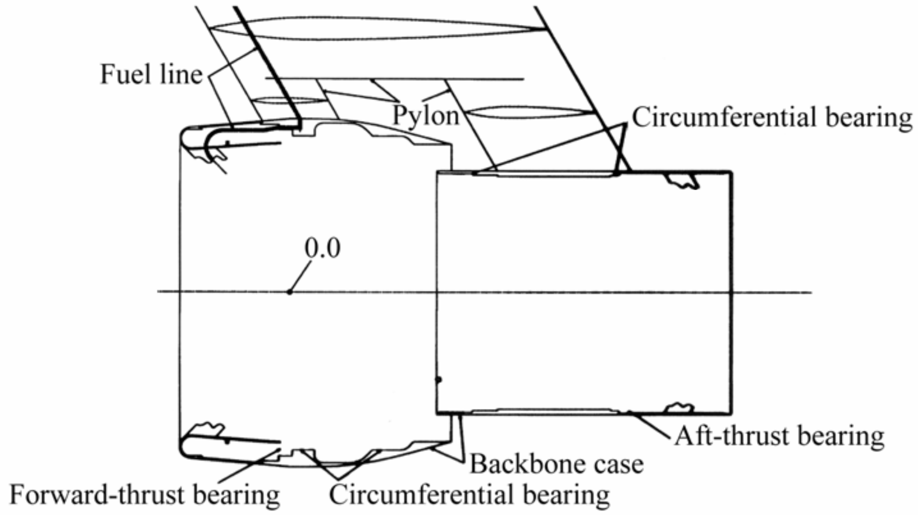


Figure 6.—Longitudinal section of exoskeletal engine exterior (backbone) shell.

Bare engine weight, lb	19 101
Accessories weight, lb	1 745
Total engine weight, lb	20 847
Inlet/nacelle weight, lb	1 509
Total engine pod weight, lb	22 357
Engine length, in.	215.8
Total engine pod length, in.	276.1
Engine maximum diameter, in.	127.0
Nacelle maximum diameter, in.	155.5
Engine pod center of gravity location, in.	96.2

Component	Number of stages	Weight, lb
Inlet	0	1510
Fan	1	2651
Splinter	0	8
Duct	0	9
Low-pressure compressor	3	1459
Duct	0	243
High-pressure compressor	10	2550
Duct	0	14
Preburner	2	508
High-pressure turbine	0	1808
Duct	0	31
Low-pressure turbine	6	6218
Duct	0	39
Nozzle	0	492
Duct	0	0
Nozzle	0	1955
Shaft	0	296
Shaft	0	827

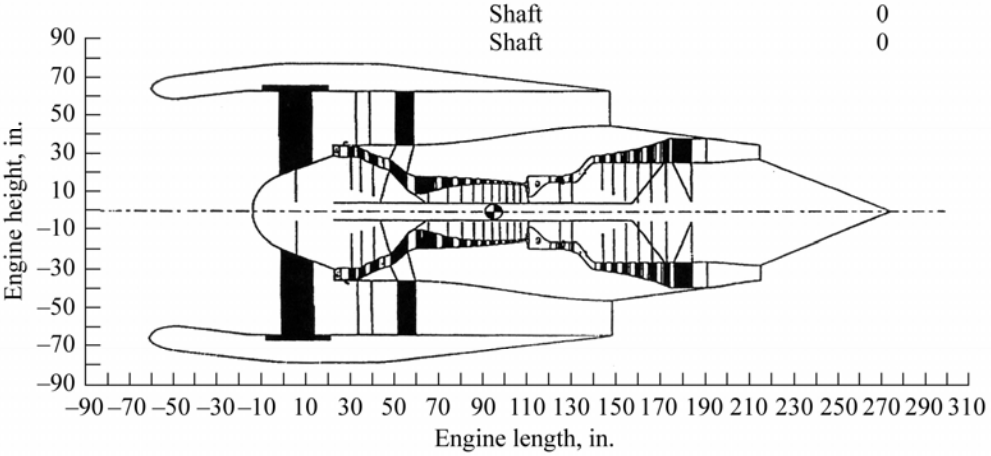


Figure 7.—Geometry and weights of baseline engine used for configuring exoskeletal engine and for comparisons. (1 lb = 4.45N; 1 in = 2.54 cm)

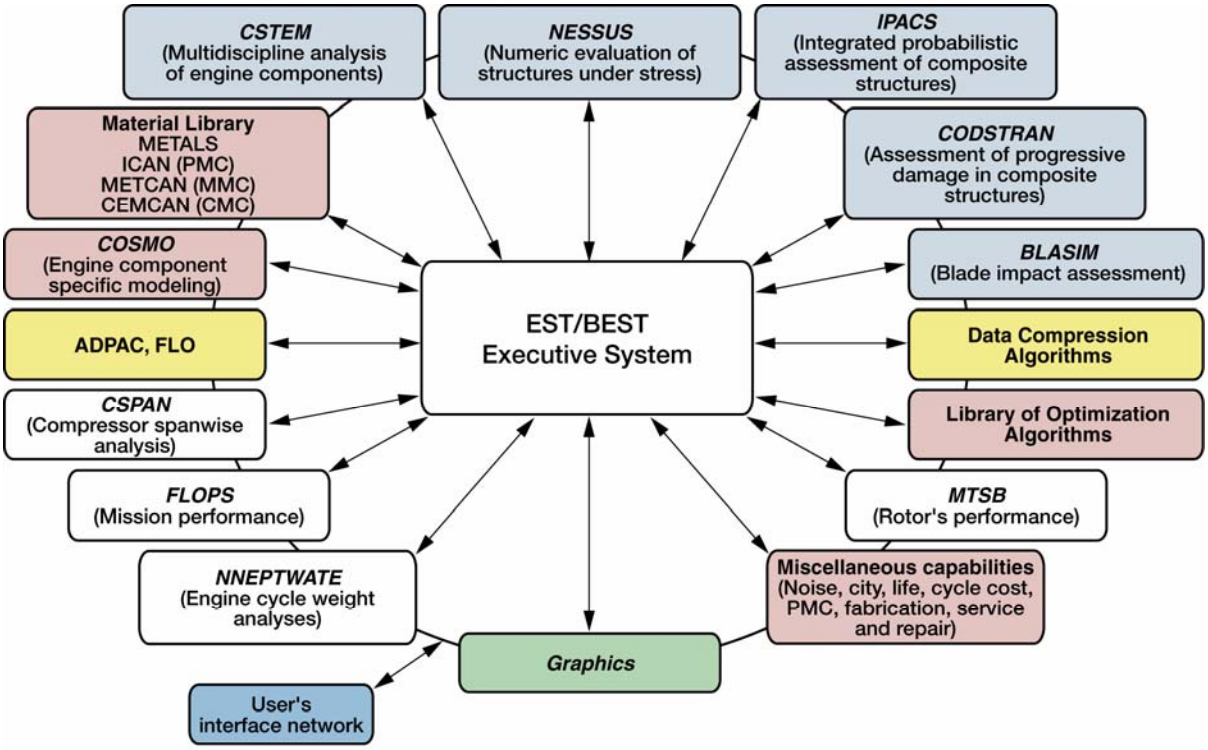


Figure 8.—EST/BEST Engine Structures Technology Benefits Estimator computer code.

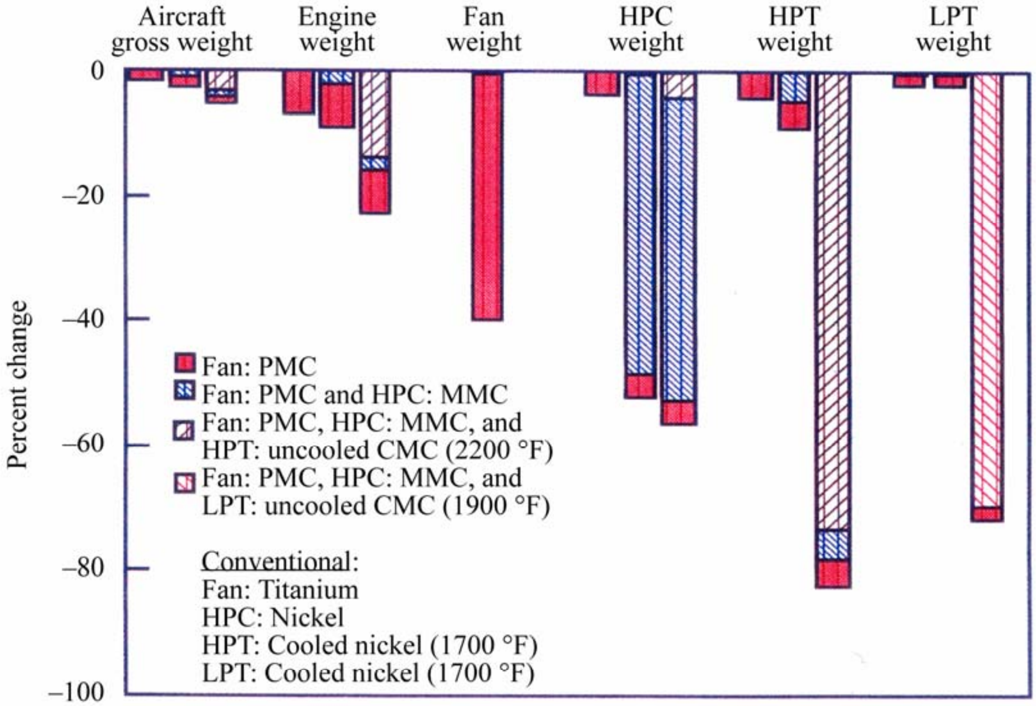
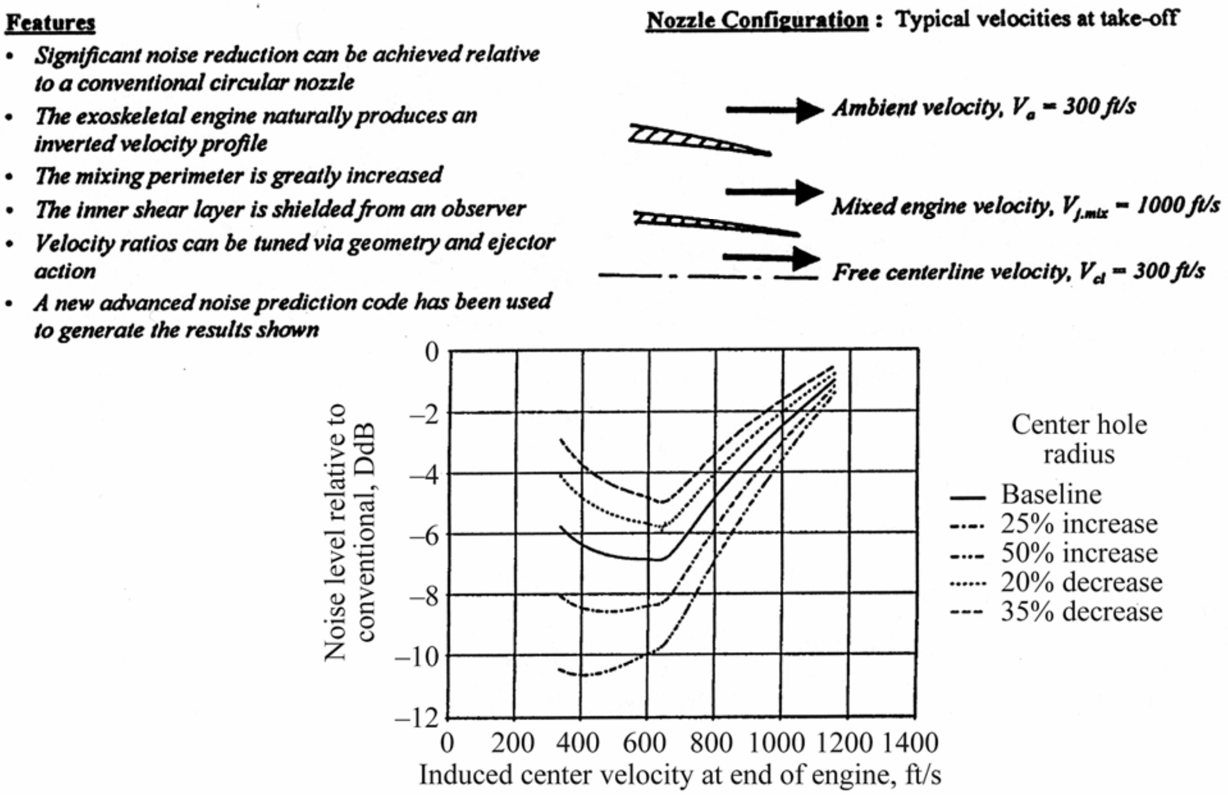


Figure 9.—Weight benefits of using polymer matrix composite (PMC) for fan, metal matrix composite (MMC) for compressor, and uncooled ceramic matrix composite (CMC) for turbines. HPC is high-pressure compressor; HPT, high-pressure turbine; and LPT, low-pressure turbine. (1 lb = 4.45N; 1 °F = 5/9 °C)



Features

- *Significant noise reduction can be achieved relative to a conventional circular nozzle*
- *The exoskeletal engine naturally produces an inverted velocity profile*
- *The mixing perimeter is greatly increased*
- *The inner shear layer is shielded from an observer*
- *Velocity ratios can be tuned via geometry and ejector action*
- *A new advanced noise prediction code has been used to generate the results shown*

Figure 10.—Noise reduction potential of exoskeletal engine concept.

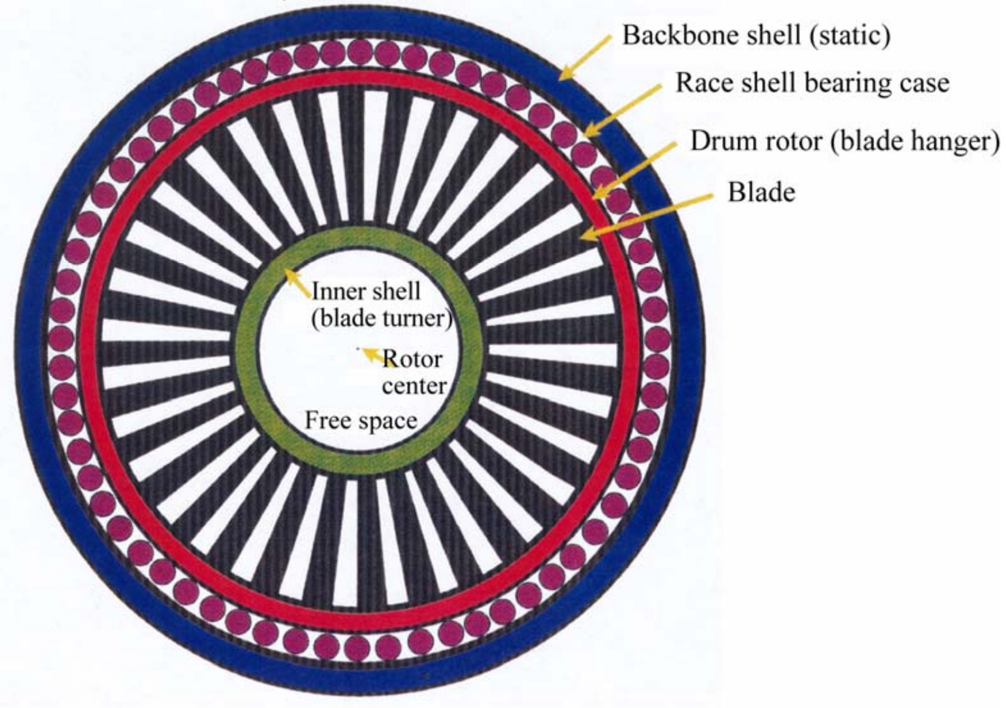


Figure 11.—Possible configuration of exoskeletal engine all-composite drum-rotor section.

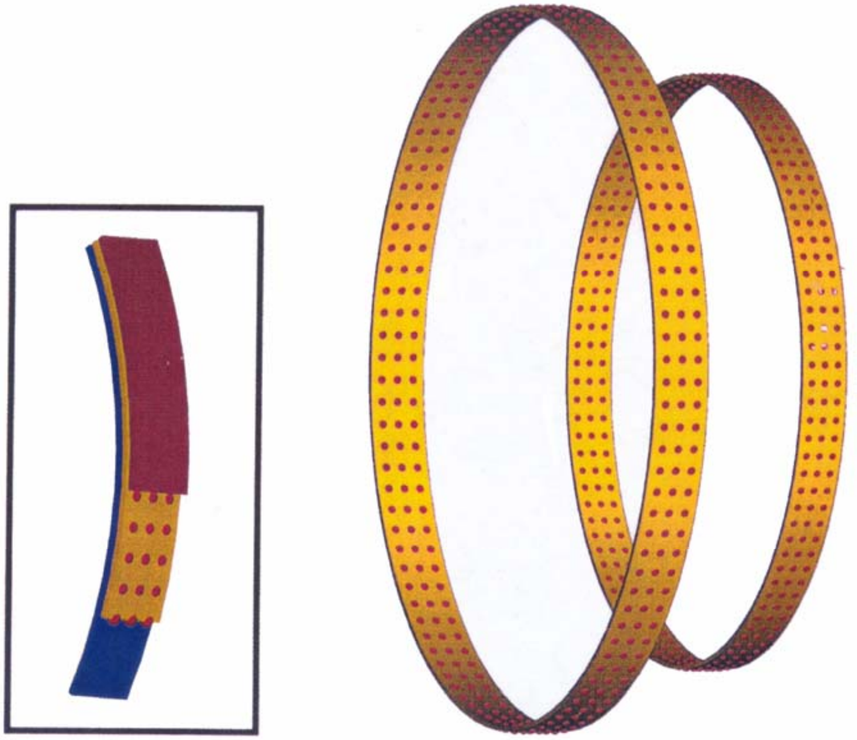


Figure 12.—Possible configuration of exoskeletal engine radial ball bearings.

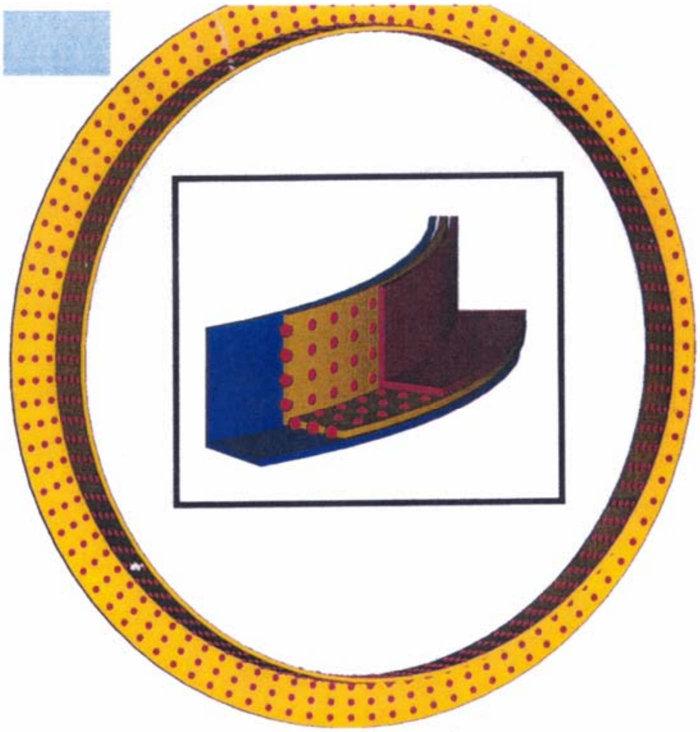


Figure 13.—Possible configuration of exoskeletal engine thrust ball bearings.

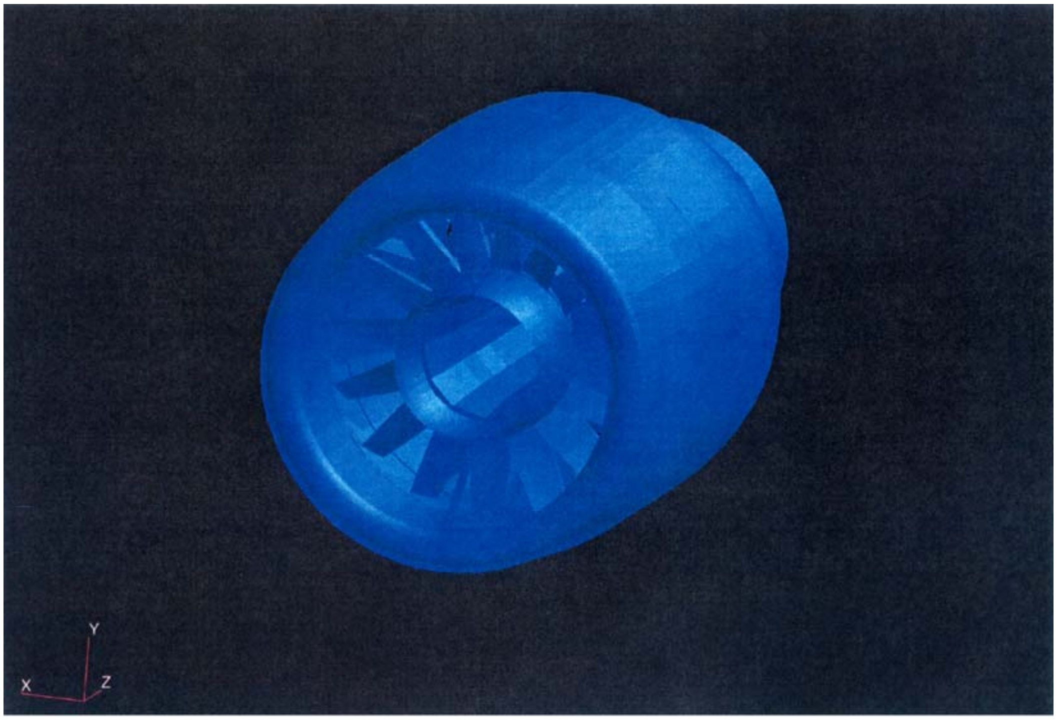


Figure 14.—Finite element model of assembled exoskeletal engine.

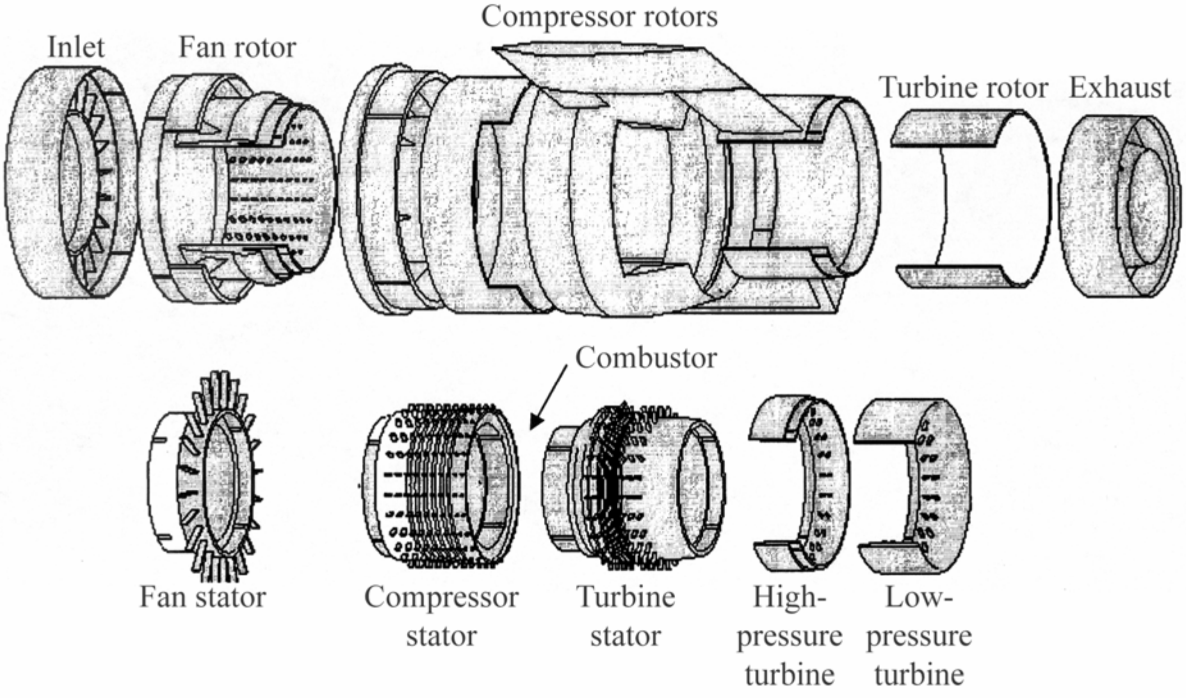


Figure 15.—Potential exoskeletal engine unitized fabrication.

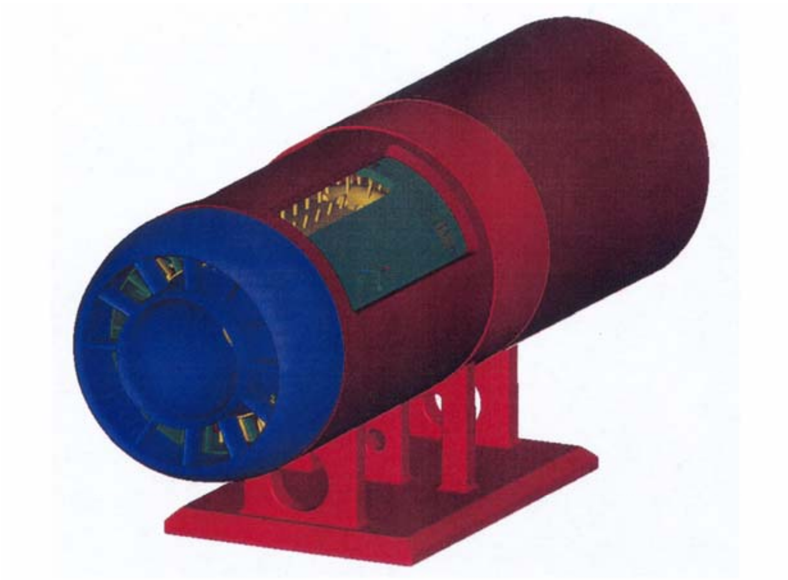
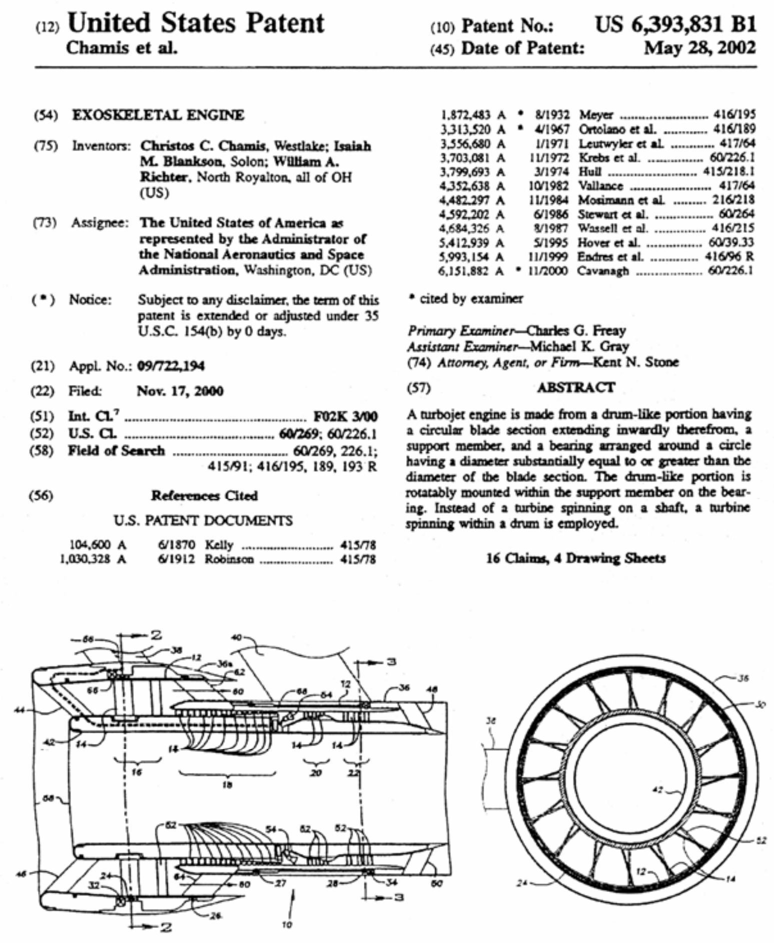


Figure 16.—Exoskeletal engine rapid prototype model.



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Chamis et al.

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(54) **EXOSKELETAL ENGINE**

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(52) **U.S. Cl.** **60/269**; 60/226.1
(58) **Field of Search** .... 60/269, 226.1; 415/91; 416/195, 189, 193 R

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(57) **ABSTRACT**

A turbojet engine is made from a drum-like portion having a circular blade section extending inwardly therefrom, a support member, and a bearing arranged around a circle having a diameter substantially equal to or greater than the diameter of the blade section. The drum-like portion is rotatably mounted within the support member on the bearing. Instead of a turbine spinning on a shaft, a turbine spinning within a drum is employed.

16 Claims, 4 Drawing Sheets

Figure 17.—First page of patent issued for exoskeletal engine.