Investigation of novel propulsion systems – the exoskeletal engine concept. Part II

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Abstract: *The exoskeletal engine represents a relatively new concept in the world of propulsion systems. It is a drum-rotor engine concept in which conventionally heavy shafts and discs are eliminated and replaced by rotating casings that support the blades in span wise compression. Thus the rotating blades are in compression rather than in 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. This is the second part of the article.*

Key Words*: exoskeletal engine, novel propulsion systems, high temperature composite materials, hybrid materials/structures.*

1. THE BEARINGS

The exoskeletal engine concept requires large-diameter radial bearings on the outside diameter of the rotating drum located at both ends of the spool. A thrust bearing is located near the outside diameter at the inlet side of the compressor spool. The large diameter coupled with the high rotational speed poses significant challenges for bearing technology. State-of-the-art bearings for conventional engines with lubricating systems can operate at very high revolutions per minute and not exceed state-of-the-art rotational speed, which is approximately 4 M DN. In the case of the exoskeletal high-pressure spool, the bearings operate at 7 M DN, well beyond the state of the art. Different alternatives for the bearing system that would be used in such a complex propulsion system have been considered. In the end, three solutions were submitted to analysis (1) the ball bearings made from graphite-carbon composite, (2) the foil bearings and (3) the magnetic bearings.

Ball bearings made from graphite-carbon composite.[5] – The reason for considering this type of bearing 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. In order to keep the radial growth close to zero we assume that the entire radial load from the rotating shell is transferred through the bearings to the outer backbone shell. A multiple row of ball bearings is envisioned as shown in Figure 1 for the radial bearings and in Figure 2 for the thrust bearings. It is evident that a number of rows can be selected in order 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

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loaded. Both of these are challenges that need to be overcome in the detail design of the exoskeletal engine.

Foil bearings. – The foil bearings as shown in Figure 3 are non-contacting and ride on a thin film of air, which is hydro-dynamically generated by the rotational speed. Lightweight foils are used in order to suspend and center the shaft. The current state-of-the-art size for this type of bearing is about 4 in diameter [1, 7]. Typical foil bearing applications use a single foil rolled around the shaft as seen in figure 1.

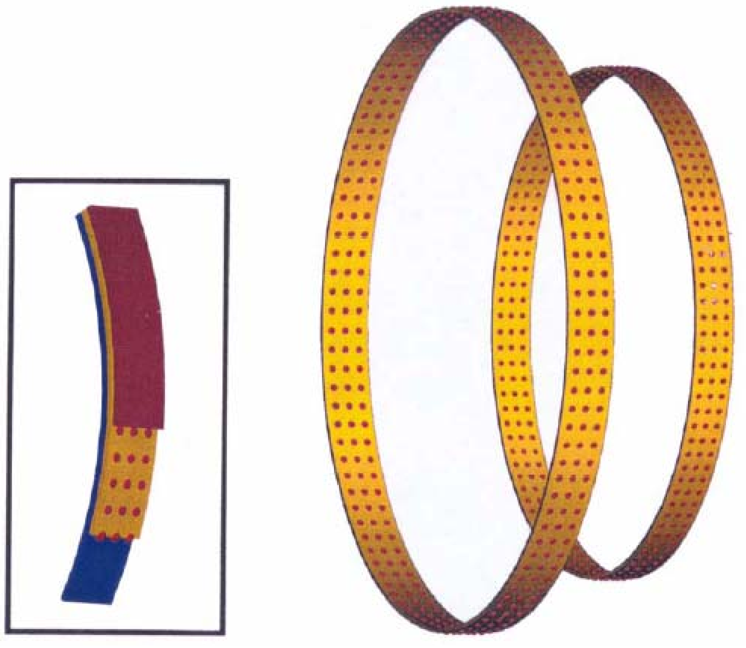

Figure 1. – Possible configuration of exoskeletal engine radial ball bearings

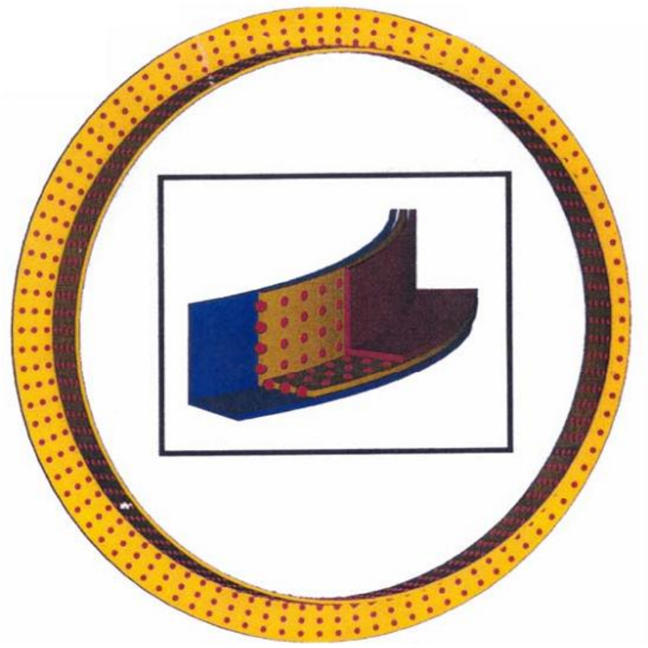

Figure 2. – Possible configuration of exoskeletal engine thrust ball bearings

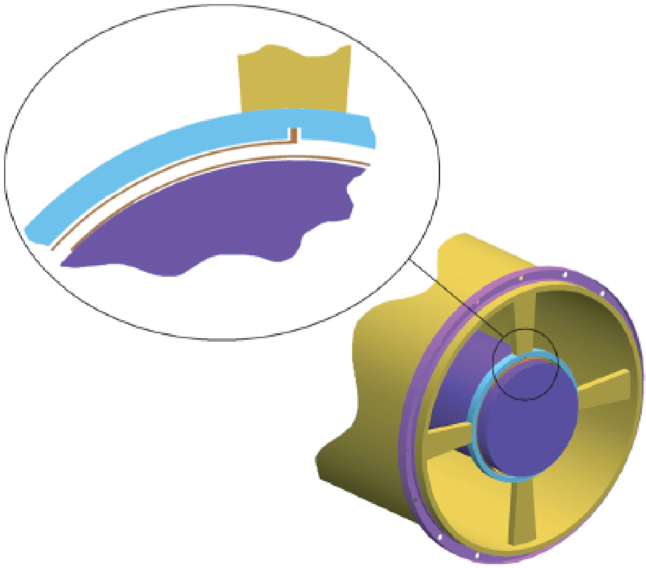

Figure 3. – Typical single foil bearing

Competing foil bearing design technology employs a bumped foil to suspend the shaft. For the large diameter application on the exoskeletal engine architecture, a hybrid system is envisioned in which the bumped foil provides stiffness and multiple foils are used to keep the large-diameter shaft centered; this is shown in Figure 4. Both the complexity of the design and the significant increase in diameter lead to a significant and long duration technical effort. Some of the drawbacks for the foil system include the high startup torque, the need for set-down/lift-off mechanical bearings and associated positioning hardware to accommodate anticipated duty cycle requirements.

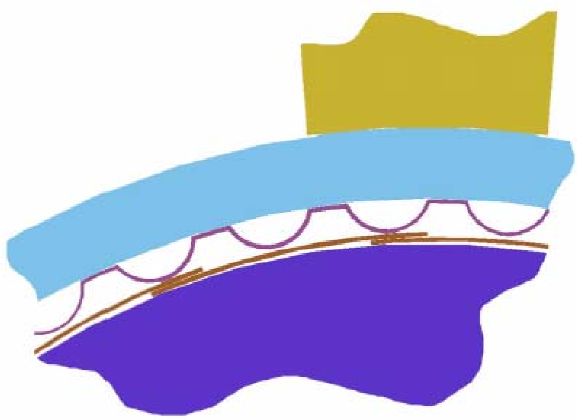

Figure 4. – Hybrid foil bearing

Magnetic bearings. – In the case of a magnetic bearing system, there are some advances in this area of research and development (R&D). Most of this R&D, however, has been focused on a small-diameter shafts that may be completely encased by a magnetic bearing housing. For the large diameter shafts in the case of exoskeletal engines, it was considered that a passive rotor may be applicable with a minimum of four electric magnetic poles at 90° apart, as shown in Figure 5. The stiffness of the large-diameter system and radial growth after spin up are among the technical challenges to overcome. Consequently, a magnet pole positioning system would be required to maintain the appropriate clearances for the operation of the magnetic bearing system. This positioning system would require high speed sensing and positioning. This would most likely leads to an increase in weights.

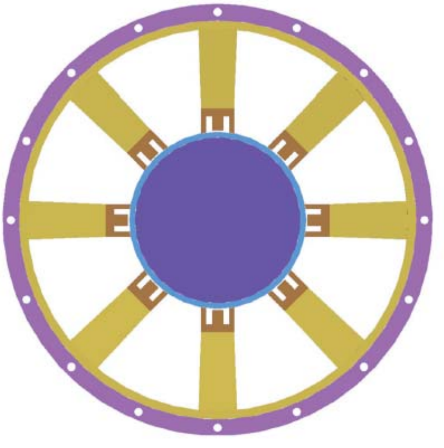

Figure 5. – Magnetic bearing

2. CONCLUSIONS

Based on the preliminary results, the exoskeletal engine 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. Below in Table 1 and Table 2 some data regarding the expected characteristics and weights summary are presented. These values are consistent with the original concept (all composite engine and graphite ball bearings).

Table 1. – Exoskeletal Engine Characterization [5]

Characteristic	Sea level static	Maximum climb	Cruise
Corrected flow, N/sec	12460	13861	12700
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, mm	3429	----	-
Fan tip speed, m/sec	1143	1234	1097

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, mm	2463	-	-
Compressor tip speed, m/sec	769	828	747.5
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, K	1691	1611	1376
Thrust, kN	311.5	73.5	48.4

Table 2. – Exoskeletal Engine Weights Summary [5]

Shell name	Dimensions, mm	Blades				Thickness, mm	Weight, kg
		Type*	Stage	Number	Thickness, mm		
Inner composite shell	Length:5955 Diameter 1: 1318 Diameter 2: 1003	--	--	--	--	6.35	182
Stationary composite shell	Length:7041 Diameter 1: 1318 Diameter 2: 1003	HPC LPC HPT LPT Vane	10 3 2 5 1	1261 215 244 771 16	6.35 6.35 6.35 6.35 12.7	12.7	820
Rotating composite shell	Length:4964 Diameter 1: 3071 Diameter 2: 1887	HPC LPC HPT LPT Vane	10 3 2 5 1	1261 215 244 771 16	3.1 3.1 3.1 3.1 12.7	12.7	1147
Outer composite shell	Length:7129 Diameter 1: 3784 Diameter 2: 2260	--	--	--	--	12.7	2669
Combined shell engine assembly	--	--	--	--	--	--	4825

The next logical step in an examination of exoskeletal engine feasibility is to consider a "clean sheet" design approach to a specific exoskeletal design goal. The design of an exoskeletal system to its best advantage (especially involving changes to the engine cycle) was not attempted during this investigation. A clean sheet exoskeletal design, free of constraints driven by comparability to an existing engine, may discover alternatives that improve the weight and performance or lessen the technology challenges of the exoskeletal approach. Other applications of the exoskeletal concept have been suggested and may serve as compelling design goals. An extension of the exoskeletal approach appears in the concept of vane less counter rotating gas turbines.

Exoskeletal implementation has been shown to be reliant on advancements in bearing technology. Therefore, a critical path to exoskeletal engine consideration is through bearing technology advancement. It is recommended that consideration of exoskeletal requirements be added to goals for high-diameter rotation-speed aerospace bearing technology programs. For comparison, below in Tabel 3, the exoskeletal high-pressure spool with a foil bearing system provides no weight advantage over a conventional design. The exoskeletal high-pressure spool with magnetic bearing system weighs significantly more than the conventional design. This weighs take into account the expected weight savings that could be realized if a conventional engine were to make use of ceramic materials and switch to integral bladed disks.

Tabel 3. – Weight comparison [All weights are in kilograms] [5]

Conventional		Exoskeletal with magnetic bearings		Exoskeletal with foil bearings	
Rotor HPC HPT Total	 84.8 31.1 121.1	Rotor drum	64.6	Rotor drum	64.6
Stator HPC HPT Total	 50.3 24.5 74.9	Stator	45.5	Stator	45.5
Bearings Shaft Bearings Total	 27	Bearing system Housings E-coils Position motors Controllers Permanent magnets Backup bearings Total	21.1 43.9 43 13.6 24.6 34 180.3	Bearing system Housings Auxiliary power unit Compressor Manifolds Total	21.1 38.1 19 10.8 89.1
Weights savings Material change Bladed disk design Total	 17.5 4.53 22				
Total system weight	201	Total system weight	290.7	Total system weight	199.4

These findings reveal that the conceptual exoskeletal rotor and stator can be lighter than their conventional counterparts, subject to the assumptions and conditions of this study. However, the integrated exoscheletal high-pressure spool system is as heavy as or is heavier than its conventional counterpart primarily because of the bearing system mass.

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