# FEASIBILITY OF MAGNETIC BEARINGS FOR ADVANCED GAS TURBINE ENGINES*

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## ABSTRACT

The application of active magnetic bearings to advanced gas turbine engines will provide a product with major improvements compared to current oil lubricated bearing designs. A re-thinking of the engine rotating and static structure design is necessary and will provide the designer with significantly more freedom to meet the demanding goals of improved performance, increased durability, higher reliability, and increased thrust-to-weight ratio via engine weight reduction. The product specific technology necessary for this high speed, high temperature, dynamically complex application has been defined. The resulting benefits from this innovative approach to aircraft engine rotor support and the complementary engine changes and improvements have been assessed.


## INTRODUCTION

The aircraft gas turbine engine represents the most challenging application of active magnetic bearings. It is the most technologically advanced, high speed rotating machinery operational in the world today. Compared to all other turbomachinery, the gas turbine engine demonstrates higher levels and larger cyclic variations of stress and temperature primarily because of the stringent requirements for thrust/weight, fuel consumption, reliability, and durability. Rolling element bearings, both ball and roller, have always been used for turbojet and turbofan gas turbine engine main shafts because of their long service life, high load capacity, tolerance to oil contamination, and their survivability to short-term loss of oil. A change from this fundamental and proven technology will only result if significant benefits of a better technology can be demonstrated and if the limits of rolling element bearings are reached.

Studies made by Pratt & Whitney and the U. S. Air Force have shown the feasibility of using main shaft active magnetic bearings as a replacement for oil lubricated rolling element bearings in advanced military aircraft engines. The studies have also shown that significant benefits including weight reduction, improved performance, improved durability, reduced external vibration, and unlimited bearing life are possible. Technology readiness by the turn of the century can be achieved by maturing existing technology. Magnetic bearing technology has advanced significantly in the past 25 years, particularly in recent years with digital controls, higher power density, and more power-efficient designs. Magnetic bearings have been applied successfully to over 100 large ground-based turbomachines such as natural gas compressors, turbo expanders, and gas, steam, and water turbines. This equipment is in operation worldwide and has demonstrated high reliability, improved performance, durability, and unexcelled vibration control with many years and hundreds of thousands of hours of successful operation. Large ground-based turbomachinery, among the 1500+ pieces of rotating equipment with magnetic bearings operating today, are cited because of their similarity to gas turbine engines. While these machines with S2M or MBI magnetic bearings compare well with gas turbine engines in size, weight, power, speed, thrust and radial loads, and general operation, there are major differences in gas turbine engine operating temperatures, dynamic loads, and other factors unique to flight conditions. It is these unique requirements that need to be addressed during the next ten years.

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The need for an improved bearing for gas turbine engines has evolved from future fighter aircraft requirements of increased thrust-to-weight ratio over the best engines available today. A 100% increase in this important engine parameter must be achieved while increasing fuel efficiency in order to increase range, improve engine component durability, and reduce life-cycle cost. To achieve these goals, the Air Force has embarked on a major long-range initiative. The Integrated High Performance Turbine Engine Technology (IHPTET) Initiative is aimed at developing the technology necessary to meet future weapon system propulsion requirements. Aggressive propulsion system goals have been jointly established by the Air Force and Pratt & Whitney and have set the focus of the engine component technology initiatives. Conceptual far-term engine designs have been initiated to determine the overall engine cycle flow path geometry and technology features that are needed to satisfy the above goals. These studies have indicated that the resulting rotor speeds will be significantly increased over the current state-of-the-art designs. Consequently, unconventional main shaft support systems, such as magnetic bearings that are able to operate at higher speeds and temperatures, become very desirable. In addition, magnetic bearings have better damping characteristics than squeeze film dampers to control shaft dynamics and reduce engine vibration.

Advanced engine designs which are being studied under the IHPTET Initiative will require advancements in rolling element bearing technology that may not be possible within the required time frame. Rolling element bearings used in current production engines are operating at speeds up to 2.4 million DN (DN = shaft diameter in mm x shaft rpm). With the recent development of a high fracture tough bearing material (M50 NiL), it is now feasible to operate rolling element bearings at speeds up to 3.0 million DN. The advanced engine designs being studied under the IHPTET Initiative will require the bearings to operate well above 3.0 million DN and at temperatures that exceed the bearing material capability (hot hardness) and the liquid lubricant thermal stability. Bearing compartment seal durability will be adversely affected by a high temperature environment, and higher engine speeds will produce higher seal sliding velocities and cause seal wear problems. Blade tip and labyrinth seal designs will have to be improved to control operating clearances. In addition, these engines will require bearings that have superior fatigue life and better damping characteristics. Magnetic bearings have the potential for meeting these requirements since they do not require a liquid lubricant and there is no physical contact between the rotor and the mount structure. Consequently, there is no wear mechanism to limit operational life.

Contained herein are the results of the Air Force sponsored magnetic bearing feasibility program. It includes, in addition to the potential benefits of gas turbine engines with active magnetic bearings, the results of a literature search which was conducted to define the state of the art, a feasibility study wherein advanced magnetic bearings were designed for an advanced military aircraft engine, and a technology requirement assessment which defined the technology necessary to further enhance the application of magnetic bearing rotor support systems for Air Force propulsion needs.

## POTENTIAL BENEFITS OF GAS TURBINE ENGINES WITH ACTIVE MAGNETIC BEARINGS

The active magnetic bearing represents an innovative approach to aircraft engine rotor support with the potential to provide significant benefits not possible with rolling element bearings. An engine with a full complement of radial and thrust magnetic bearings combined with electrical accessories would add a new dimension to the design of aircraft gas turbine engines. This magnetic bearing engine would incorporate many electrical components, some of which are necessary because of the elimination of a mechanical power takeoff, i.e., the tower shaft and the accessory gearbox. An integral, main shaft starter/generator and electric fuel pumps for both main and augmentor supplies are required. Other components such as electric vane and nozzle actuators become attractive for this "mostly" electric engine. The successful application of magnetic bearings would result in future engines with the following features:

- Reduced engine weight
- Elimination of oil and hydraulic systems
- Improved fire/safety survivability
- Simplified, less costly bearing compartment seals

- Elimination of the tower shaft
- Elimination of the accessory gearbox
- Higher rotor speed potential
- Reduced blade tip and seal clearances
- Reduced rotor-to-case deflections due to aircraft maneuvers
- Reduced secondary airflow for cooling and thrust balance
- Reduced bearing power consumption
- Superior engine vibration response control
- System health monitoring
- Virtually unlimited bearing life.

These features would reduce the propulsion system fuel consumption and maintenance requirements, and increase thrust-to-weight and reliability, thus providing greater aircraft capability with lower life cycle cost. The improvements in reliability, durability, and vibration control are exemplified by the dramatic change in the engine external components relative to a conventional engine of today, as is shown in Figures 1 and 2. The incorporation of magnetic bearings and other electrical components will produce an engine with significantly less plumbing and mechanical structure which is susceptible to vibration and fatigue failure. The elimination of a majority of the failure-prone hardware alone will provide a greater than 2:1 improvement in reliability. With the anticipated superior vibration control of magnetic bearings, the durability of the remaining structure (e.g., fuel and bleed air lines) will be significantly improved. Improvements in maintainability of the external engine structure are readily apparent primarily because of the resulting simplicity. The remaining components only include the engine and magnetic bearing electronic control system, electric fuel pumps and associated delivery systems, electric actuators, and the air bleed and service systems.

## Increased Thrust-to-Weight Ratio

Among the most fundamental means to increase engine specific thrust and, therefore, thrust-to-weight is to increase the speed of the rotating components in the engine. Since the aerodynamic work interactions of the turbomachinery within the engine are proportional to the square of the tip speed of the blading, increased rotational speed has a dramatic effect on the performance of an engine. The stress levels in the blading material also increase with the square of the tip speed, thereby requiring improved materials with increased working stress levels and reduced densities. The current operating speed capability of rolling element bearings used in today's engines could be increased to values of 3.0 million DN if improvements in lubrication technology and the materials used in the elements, races, and cages are realized. While progress in rolling element bearing technology will continue, active magnetic bearing systems have already demonstrated DN values of more than 4.5 million, a significantly higher level. The limitation of operating speed and DN of a magnetic bearing is dependent upon centrifugal stresses generated in the materials used for rotor construction, and does not involve the frictional heating and fatigue limits associated with rolling element bearings. Considering recently demonstrated developments in magnetic bearing technology, step increases in rotor speed and gas turbine engine performance are believed to be achievable within the time frame consistent with IHPTET Initiative goals. Thus, higher speed, longer life turbine engines are achievable with active magnetic bearings.

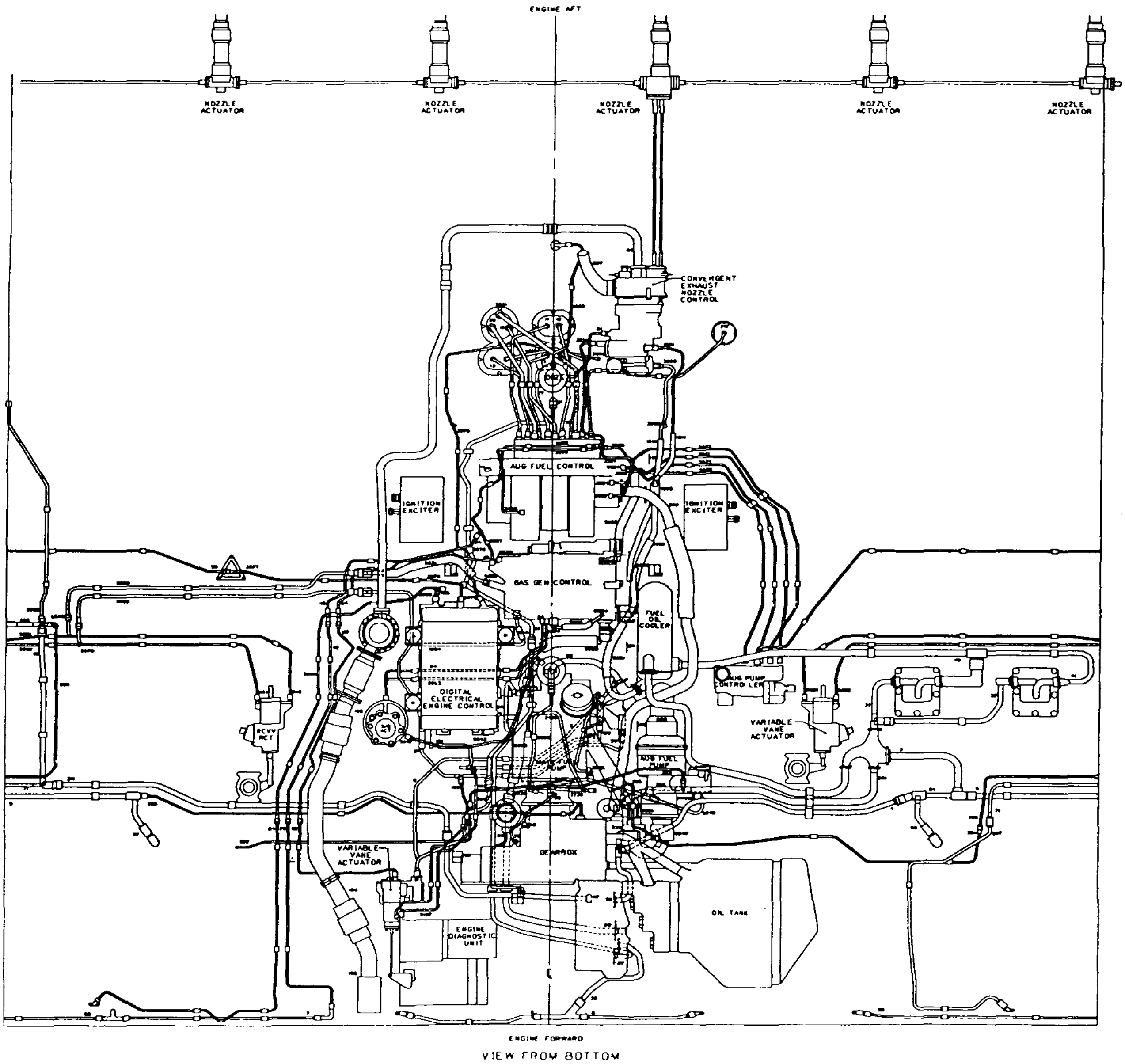


Figure 1. Conventional Engine External Components

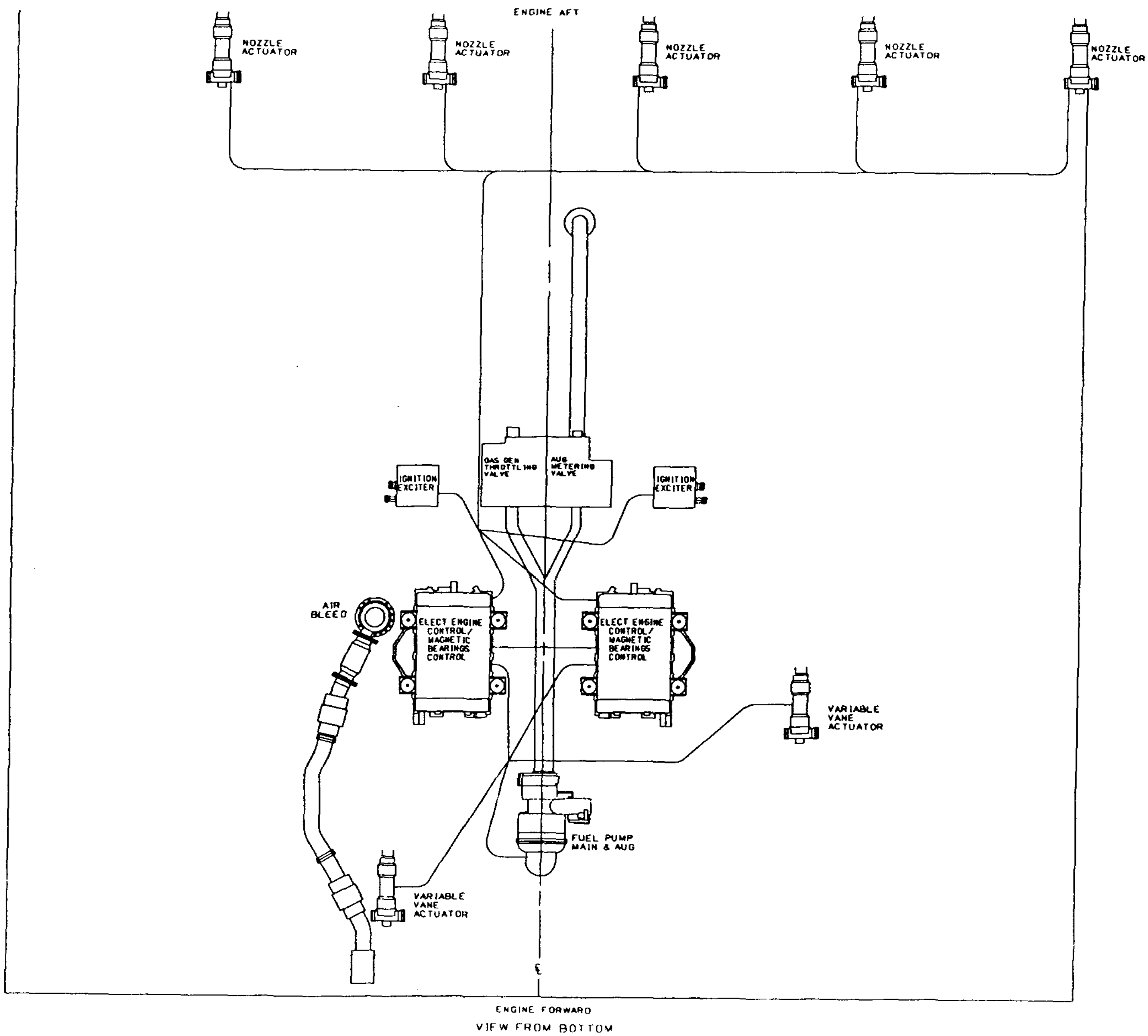


Figure 2. Magnetic Bearing Engine External Components

Design and Aerodynamic Advantages

The higher DN capability of magnetic bearings will increase the allowable bearing-limited speed for a shaft of a given size, or permit larger shafting for a specific operational speed, thus increasing shaft stiffness and providing more design freedom. Since magnetic bearings do not require lubrication, the overall engine design could be quite different. No oil tank, supply or scavenge pumps, oil piping or coolers would be required. Weight savings and additional design freedoms could accrue. Bearing compartment temperature limits related to lubricants could be raised significantly since magnetic bearings can be made to operate in temperature environments exceeding 1000°F if magnetic material and insulation research continue to extend the temperature range of the most promising materials. Further design advantages in the use of magnetic bearings for aircraft gas turbine engines are possible by electronically varying the stiffness and damping of each bearing. The rotor could be made to rotate about the inertial axis rather than the geometric axis, and thereby reduce the structural vibration caused by rotor imbalance. The axial position of the rotor could also be controlled by the magnetic thrust bearing. With more sophisticated digital controller algorithms, it will be possible to improve performance by closing blade tip and seal clearances in a manner similar to currently employed thermal methods, but more efficiently.

### Operational Impact

Magnetic bearings in a high performance turbine engine will provide important operational benefits. The elimination of lubrication oil in an all-magnetic bearing engine has logistic and supply advantages, and eliminates the need for filters and the possibility of contamination. It also eliminates oil servicing and sampling. Bearing life is essentially unlimited, and higher temperature operation is possible. Energy losses associated with the friction and the lubrication systems in rolling or sliding element bearings are eliminated; the electrical power required for magnetic bearing operation is relatively small. Signals for system diagnostics already exist in the electronic control of the magnetic bearing. Both the radial and axial bearing control sensors may be used not only for vibration and position control, but also for monitoring imbalance level. As rotor imbalance increases due to erosion or foreign object damage, the levels can be monitored to prevent set limits from being exceeded. Signals proportional to bearing current can be used as measures of bearing load. Using these data, the net axial thrust load on the rotor can be determined. With magnetic bearings, improvements in engine health monitoring will be possible.

## LITERATURE SURVEY OF MAGNETIC BEARING TECHNOLOGY (1988)

A literature survey, which identified and defined the current state of the art relative to design, analysis, manufacture, operability and use of magnetic bearings, focused on bearing load capacity, damping characteristics, electronic control systems, power requirements, and size and weight of both the bearing and the control system. Of prime importance was determining future development trends in digital control technology, high saturation flux magnetic materials, high temperature insulation materials, and high strength rotor lamination materials. The literature survey showed three types of magnetic bearings: passive, active, and hybrid concepts. Passive magnetic bearings employ high-energy permanent magnets configured either for repulsion or attraction. Because of their low load capacity and lack of damping, these bearings were not considered suitable for aircraft engine applications. Active magnetic bearings of the "attractive force" type are the dominant design in most commercial installations. They employ closed-loop analog control systems. Hybrid magnetic bearings use both permanent magnets and electro magnets wherein the permanent magnets generate the static (bias) force and the electro magnets generate the dynamic force. Negative features of hybrid bearings are low stiffness and the need for larger air gaps to control permanent magnet related stabilities. However, because of the lower power consumption requirements, imaginative hybrid design configurations could have the potential to enhance significantly the application of these bearings for aircraft engine applications (Ref. 1). Because the current design philosophy of commercially operating active magnetic bearing systems is dictated by land-based applications, size and weight considerations do not play a primary role. These magnetic bearings and analog control systems are bulky and heavy and are not suitable for aircraft engine applications. The literature survey has, however, revealed that advanced magnetic materials, such as Supermendur, and coil current densities similar to those presently achieved in aircraft electric power generators can be used to design magnetic bearings with significant size and weight reductions necessary for aircraft engine applications. Order of magnitude reductions in control system size and weight are also achievable by replacing the analog controls with digital controls. Miniaturized digital controls with adaptive algorithms, which are necessary for the dynamically complex gas turbine engine, can be developed. These developments in control technology have the potential to provide weight and size reductions of the electric generators, heat exchangers, power amplifiers, and even the magnetic bearing structure. Key development areas, which are critical for the advancement of magnetic bearing technology for aircraft engines, include: magnetic bearing control technology, high saturation flux magnetic materials, high temperature insulation materials, and high strength rotor lamination materials. Major conclusions on each of these areas are discussed below.

### Magnetic Bearing Control Technology for Aircraft Gas Turbine Engines

Most magnetic bearing controllers use analog circuits which have inherent size, weight, and versatility disadvantages. Digital controllers, however, have the potential to overcome many of the drawbacks associated with analog controllers and, therefore, will be more suitable for aircraft engine applications. Significant development effort would, however, be required before a miniaturized digital control system can be produced. The previously uncompetitive weight and size of magnetic bearing systems, compared with rolling element bearing systems, has precluded their application to rotor support in aircraft turbine engines. This literature survey showed that the basic technology now exists for implementing an aircraft magnetic bearing system with weight and size competitive with conventional bearings. Significant reductions in the magnetic bearing design loads result from using a microprocessor implementation of a model follower control strategy having disturbance estimation and eccentricity offset capabilities (Ref. 2). By forcing the rotor geometric center to orbit around its mass center during operation at any speed (including shaft critical speeds) and with a limited degree of imbalance (including blade loss), the magnetic bearing need only be designed to withstand aircraft maneuver loads. These loads are a small fraction of the rotor imbalance loads that must be reacted. The reduced loads made possible by this new control technology would permit significant reductions in weight and size of the magnetic bearings, their control circuitry, power amplifiers, and the generators needed to power them. The application of magnetic bearing systems to support the rotors of aircraft turbine engines should result in more predictable rotor damping, nearly zero dynamic force transmitted to the support structure, elimination of most in-flight shut-downs (IFSDs) caused by high engine vibration, and improved engine reliability (dual channel electronics with no single point failure).

## High Saturation Flux Magnetic Materials

Iron-cobalt materials like Vanadium Permendur and Supermendur have immediate applications for significant size and weight reductions in active and hybrid magnetic bearings. Magnetic saturation flux densities of 2.4 teslas appear possible (Refs. 3-5). Thus, with small air gaps (10 mils), large weight reductions appear practical. Optimization design analyses will be necessary to determine achievable weight and size reductions, and development will be necessary to improve heat treatment procedures for optimal magnetic and mechanical properties.

## High Temperature Insulation Materials

State-of-the-art high temperature winding insulation materials are ceramics, polyimides, polyesters, silicones and epoxy Novolac. While ceramics have up to 2000°C maximum useful temperature, the other high temperature insulation materials have maximum useful temperatures between 250°C and 315°C. Cracking problems in the ceramic and epoxy encapsulants may be handled using special curing schemes and fillers including glass microspheres. Vacuum pressure impregnation can eliminate cracking problems but provides less mechanical and chemical protection for the windings. Numerous IEEE and ASTM standard test procedures for electric rotating machine insulation may be used to evaluate high temperature insulation systems for active magnetic bearings. When operating requirements are specified, appropriate insulation can be selected and developed to provide the required life for aircraft engine environmental conditions.

## High Strength Rotor Lamination Materials

Iron-cobalt-vanadium-nickel and specially heat treated iron-cobalt-vanadium alloys appear to be very attractive high speed rotor lamination materials. Flux densities of 2 teslas at 50 to 100 oersteds and yield strengths of 100,000 psi have been reported (Ref. 6). A commercially available iron-cobalt-vanadium-nickel alloy is Rotelloy, but the properties of Rotelloy are not well documented. Reported values of mechanical and magnetic properties were not referenced to any standard test procedures. Currently available alloys appear to be adequate for high DN rotor applications, but it will be necessary to document the heat treatment procedures and the reported mechanical and magnetic properties.

# ENGINE AND MISSION SELECTION FOR THE FEASIBILITY STUDY

Under an Air Force sponsored program, Pratt & Whitney conducted configuration definition and long-range planning studies to define required propulsion system technologies for future weapon systems. The study involved extensive Pratt & Whitney and airframer coordination to meet the IHPTET goals of doubling current propulsion system capability. Representative advanced engine preliminary designs capable of meeting the IHPTET goals, and realistic missions for these engines were selected. Mechanical component operating conditions were also predicted. A far-term advanced engine, which had been optimized for a Mach 3.0 Interceptor Aircraft, was selected for the magnetic bearing feasibility study. The magnetic bearing system requirements in terms of bearing loads, bearing compartment size, operating temperature, bearing stiffness and damping, and shaft diameter and rotational speeds were predicted. These design requirements were dictated by the selected mission profile. This engine was selected for the magnetic bearing feasibility study because the bearing compartment temperatures and bearing loads were much higher than other engines, thereby dictating an advanced level of magnetic bearing technology to meet these stringent requirements.

The far-term engine conventional bearing design incorporated five main shaft bearings, one of which was an intershaft roller bearing. Because it appears not to be technically feasible to incorporate an intershaft magnetic bearing, a modification to the engine bearing arrangement was made. The bearing was changed from intershaft to a conventional case supported radial bearing. This is the arrangement for which the operating conditions were predicted. Specifically, the bearing damping and stiffness, maximum load, maximum operating temperatures, and bearing compartment constraints were used for the design of magnetic bearings for advanced IHPTET engines.

## FEASIBILITY STUDY

The purpose of the feasibility study was to apply the knowledge gained from the literature survey and determine if magnetic bearings could be designed under the conditions and within the constraints imposed by the selected engine and mission. The literature survey provided the current level of technology and offered insight into possible advancements in required technology areas such as digital controls, high temperature winding wire insulation, high strength rotor lamination materials, and high saturation flux magnetic materials. The selected far-term engine (Figure 3), which had the requirement of meeting IHPTET goals, was a particularly challenging target because of very high rotor speed, high bearing compartment operating temperatures, and high rotor thrust. In addition, space was at a premium for both the bearing compartments and the externally mounted digital electronic control. By applying state-of-the-art technology, it was concluded that a practical design which would meet advanced military aircraft engine requirements could not be achieved. Significant modifications including excessive cooling air requirements, the inclusion of thrust balance air, changes to the rotor construction, and the placement of generators on both rotors were necessary. This resulted in a very uncompetitive design compared to rolling element systems. An all-barriers-removed design could meet the advanced engine requirements and could be achieved by developing existing basic technology. Technology programs are essential to develop flight worthy digital controls, reliable auxiliary bearings, high power density starter/generators, high flux density magnetic materials, high temperature position sensors, and durable wire insulation. It is concluded that, with a firm commitment to the technology, the application of active magnetic bearings to military aircraft engines could be demonstrated within a time frame consistent with the objectives of the IHPTET Initiative.

### State-of-the-Art Magnetic Bearing Design

The state-of-the-art design of magnetic bearings for the far-term engine was based on the philosophy that the bearings and the integral starter generator could be built using existing technology. It was concluded that the design would not fit into the limited bearing compartment space and environment without compromising performance, weight, and engine configuration. This was based upon limitations in material properties, insulation capabilities, and the analog control systems which are well known today. The integral starter/generator also did not fit into the available space forward of the No. 2 bearing, thereby requiring an additional generator to be placed on the low rotor. The analog controller was also found to be excessively large and heavy. Table I presents a summary of the state-of-the-art magnetic bearing design dimensions. The state-of-the-art bearing dimensions as designed with the full thrust and radial load requirements were considerably beyond the bearing compartment envelopes. A reduction in the thrust bearings capabilities was necessary to fit the envelope and resulted in a compromise in the engine thrust balance system. Full rotor thrust could not be taken by the thrust bearings but needed to be offset by conventional thrust balancing which imposed a performance penalty. Minor modifications were also required in the rotating and static structure to accommodate these large bearings. The saturation flux density level of the materials used in this state-of-the-art design was based on proven technology. Levels of 1.5 teslas to 1.7 teslas were assumed and are considered entirely feasible based on experience at these levels in other electro magnetic equipment.

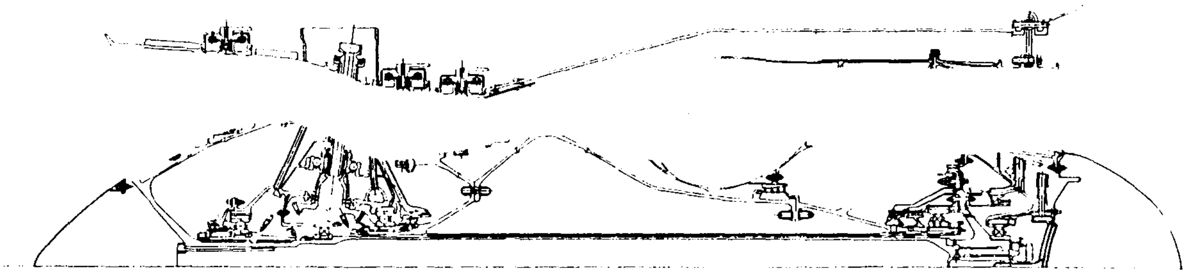

Figure 3. Conventional Bearing Engine Design

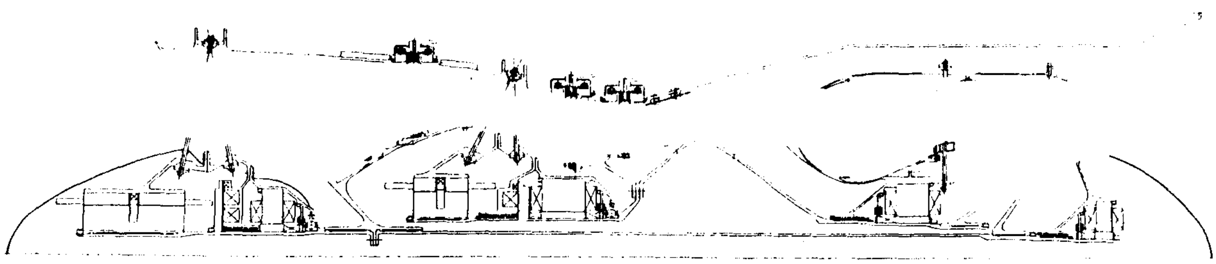

Figure 4. State-of-the-Art Magnetic Bearing Engine Design

TABLE I. STATE-OF-THE-ART AND ALL-BARRIERS-REMOVED DESIGN DIMENSION SUMMARY

| Bearing Number | Available Axial Length (inches) | Available OD (inches) | State-of-the-Art Length (inches) | State-of-the-Art OD (inches) | All-Barriers-Removed Length (inches) | All-Barriers-Removed OD (inches) |
|---|---|---|---|---|---|---|
| Radial/thrust No. 1, low rotor | 4.0 | 10.0 | 5.18 | 9.8 | 3.58 | 9.8 |
| Radial No. 4, low rotor | 3.5 | 7.75 | 3.18 | 7.7 | 1.41 | 7.7 |
| Radial/thrust No. 2, high rotor | 3.0 (4.5) | 11.0 (10.0) | 7.26 | 10.4 | 4.66 | 10.4 |
| Radial No. 3, high rotor | 3.5 | 9.5 | 4.25 | 10.1 | 1.95 | 10.1 |

The environmental temperatures in the bearing compartments (860°F, 1450°F) are considered very severe with today's proven insulation technology. While there are published data on ceramic impregnants capable of withstanding these temperatures, their use in this type of application is not proven. To keep the risk to a reasonable level, proven epoxy encapsulants were used in the state-of-the-art design. This required the use of cooling air to keep the bearing compartments under 400°F, a temperature comparable to conventional bearing compartments. Cooling air to accomplish this requires an external cooling system since ambient air can be as high as 640°F during parts of the assumed mission. A 20 mil and 15 mil radial air gap for the thrust and radial bearings, respectively, were used for the state-of-the-art design. Reduction of this gap would allow a size reduction in the bearings but would increase the likelihood of contacting the auxiliary bearings during aircraft maneuvers. With the current proven flux density capability, the 20 mil and 15 mil gaps provided a lower risk design. Nickel plated copper wire was assumed for the state-of-the-art design. This plating prevents oxidation of the copper and has been proven in a 550°F environment.

The analog electronic controller for the state-of-the-art bearing design would see temperatures in excess of 640°F if it were placed on the side of the engine without a means to cool it. An analog controller would require cooling air to create the environment currently seen by engine fuel control systems. A volume estimate of the analog controller and power switching electronics would be approximately 2.5 cubic feet. This 2 to 1 size reduction of current production controllers would be accomplished by high density packaging. However, a system this large would present a severe performance penalty if mounted on the engine within the nacelle. To minimize this performance penalty and that associated with cooling air requirements, it was assumed to be airframe mounted.

The auxiliary bearings, which are necessary for preventing magnetic bearing contact during high but temporary axial and radial loads, were designed to provide limited life during conditions such as surge, high aircraft maneuvers, or hard landings. The clearance between the shaft and the auxiliary bearing was set at one-half the magnetic bearing clearance enabling the auxiliary bearing to support the excessive load without damaging the magnetic bearing. Under conditions of prolonged heavy loading, bearing life would be severely compromised if they were not oil lubricated. The auxiliary bearings designed for the state-of-the-art magnetic bearing engine would have a life measured in minutes. This requires an engine shutdown if loads exceed the magnetic bearing support capability as would be expected during a significant blade failure. The state-of-the-art magnetic bearing engine cross section (Figure 4) shows two types of auxiliary bearings which are considered necessary for intermittent overload and safe shutdown. The sleeve bearings, consisting of dissimilar materials with high lubricity (e.g., carbon and silicon nitride), are designed to contact first and react the momentary high loading. The two solid lubricated ball bearings would provide the thrust and radial support during shutdown after a failure.

With the elimination of the oiling system, the tower shaft and external gearbox were also removed. This results in a cleaner flow path and requires the mechanically driven externals to be electrical. Starting the engine must be accomplished with a high rotor mounted integral starter/generator. Considering the temperature and space constraints imposed by the far-term engine and the selected mission, a single permanent magnet starter/generator could not be designed for the power requirements of the aircraft (250 KVA) using state-of-the-art technology. The alternative was to place a starter/generator on the high rotor and place a second generator on the low rotor forward of the No. 1 bearing in the nose cone. This also required an additional support structure at the inlet and added significant weight and complexity to the engine.

## Design Technology Shortfalls

The application of state-of-the-art magnetic bearing technology to the far-term engine did not provide a practical design that would meet all the requirements of this advanced aircraft engine. Significant modifications to the configuration were necessary and severe performance and weight penalties were anticipated. As a result of the state-of-the-art configuration study, technology shortfalls were identified in the magnetic bearing, the associated controls, the starter/generator, and the auxiliary bearings. Specifically, the shortfalls were a direct result of high environmental temperature, load and power requirements, size and weight constraints, and life requirements. Each of the items is addressed below in order to provide an understanding of the deficiencies and the development necessary to overcome these technology shortfalls.

Magnetic Bearings. The primary problems associated with the magnetic bearing are size, weight and temperature capability. Load capacity was achieved in the state-of-the-art design by increasing the size and, therefore, the weight. Load capacity measured in terms of unit volume or unit weight must be increased significantly for magnetic bearings to become practical. Significant improvements in soft magnetic materials for both the stator and the rotor lamination materials to increase the flux density are essential. The bearing compartment environmental temperature for the state-of-the-art design was assumed to be maintained below 400°F primarily because of the lack of durable, high temperature wire insulation materials. Development in this area is also required and appears to be feasible at temperatures approaching the magnetic material Curie point.

Controller. With state-of-the-art technology, the controller (analog design) is significantly heavy and too large to be mounted within the nacelle. Miniaturized digital control systems with expanded control capability are essential for advanced aircraft engine designs. Integration of this control system with the engine electronic fuel control will offer additional benefits.

Starter/Generator. The space and temperature constraints imposed by the far-term engine required the incorporation of a homopolar generator into the state-of-the-art design. This design would be capable of operating in the engine environment but only half as efficient in size and weight as a permanent magnet design; thus, the engine required an additional generator on the low rotor. The weight and performance penalties associated with this approach were expected to be unacceptable. A high temperature, high efficiency starter/generator must be developed. Advanced materials and insulation capabilities required for the magnetic bearing could also be used in the starter/generator.

Auxiliary Bearings. The state-of-the-art auxiliary bearing limitation was primarily low life. There is a need for a fail-safe backup bearing to allow, in addition to intermittent heavy loading, engine operation during failure of the magnetic bearing system. The goal of sufficient life to enable the pilot to return to base requires extensive development of a solid lubricant bearing capable of operating at temperature levels approaching 1500°F.

## All-Barriers-Removed Magnetic Bearing Design

The all-barriers-removed design of magnetic bearings for the far-term engine was based upon the philosophy that the bearings and integral starter/generator could be built within a time frame consistent with the objectives of the IHPTET Initiative by developing basic technology which exists today. It does not, for example, depend upon unexpected breakthroughs such as high temperature super-conductivity or the development of specialized magnetic materials which have Curie temperatures much greater than available today. Development in the areas cited above or in related fields is currently in progress; what is required is the extension or redirection of these efforts toward the specific needs of active magnetic bearings in the gas turbine engine application. Table I presents a summary of the all-barriers-removed magnetic bearing design dimensions.

The all-barriers-removed bearing designs were successfully incorporated into the far-term engine (Figure 5). The forward bearings (Nos. 1 and 2) were designed to operate at the maximum environmental temperature of 860°F and handle the full radial and thrust load without thrust balance air. The rear bearings (Nos. 3 and 4) were designed to operate at a maximum temperature of 1450°F in order to keep below the Curie temperature of the magnetic materials. Cooling air was required for the No. 3 bearing location where surrounding environmental temperatures exceed 3500°F. The required load capacity of these advanced bearings was achieved by assuming saturation flux densities of 2.4 teslas. Further increases in load capacity were achieved with air gap reductions to 10 mils radial, approximately half the gap of the state-of-the-art design. With advanced, adaptive digital controls, full dynamic control and stability with this small clearance should be achievable.

With the magnetic bearings operating at temperatures of 1450°F, ceramic insulation is necessary. The development of ceramic impregnation and encapsulation techniques need to be developed to guarantee the life requirements of these bearings. At high temperatures, the copper wire would experience a significant increase in electrical resistivity causing increased power consumption due to higher $I^2R$ losses. It is, therefore, desirable to keep the resistivity as low as possible either through the use of high thermal insulation, compact cooling systems, or a change of material (e.g., silver). Silver wire has been assumed for the high temperature bearing locations in the all-barriers-removed design. A miniaturized digital controller was assumed for the all-barriers-removed design. The development of a flight worthy reliable controller one-fifth to one-tenth the size assumed in the state-of-the-art design appears to be technically possible. This is based on experience obtained from engine control system designs. With a volume of 0.5 to 0.25 cubic feet, placement on the engine with cooling schemes used today for the engine digital electronic controller will make the magnetic bearing system very attractive from a weight and performance standpoint. The auxiliary bearings for the all-barriers-removed design, as shown in Figure 5, appear to be essentially the same as the state-of-the-art design. The difference lies in their temperature and life capability. Development in this important area is critical to the success of the active magnetic bearing and the schemes shown are only representative of a concept requiring extensive development. The starter/generator shown on the all-barriers-removed design is a permanent magnet design with the full capability to supply all aircraft required power. This 250 KVA system, which resides in a 640°F environment, would require development but is considered achievable within the IHPTET time frame.

## Technology Readiness Development

In order to achieve technology readiness within the IHPTET time frame, development in seven key areas is required.

### *(1) Digital Controls and Control Algorithms*

Commercially available active magnetic bearings employ analog controllers. Since these active magnetic bearings are for ground-based applications with minimal space and weight constraints, the analog controllers have not been optimized and are large and heavy. To meet the requirements of the advanced aircraft engine bearings, the controller must be engine mountable, compact, lightweight, and very reliable in addition to being adaptive and integrable with the associated engine/flight systems. These conditions determine a dictated digital control system design not available as a commercial unit. The payoffs of using digital controllers include size and weight reductions and the benefits of combining digital active magnetic bearing controllers with digital electronic engine controllers. The digital active magnetic bearing controller will lead to improved reliability without increase in size through the incorporation of redundancies in the hardware and software. Digital controllers will make it possible to take advantage of "modern" control methodologies like digital filters for replacing lead compensation networks. Finally, digital controls can employ unusual control algorithms to improve system performance and not be limited to traditional control approaches like proportional-integral-derivative circuits. Considerable development work will be necessary to provide a fault-tolerant, miniaturized military quality digital active magnetic bearing controller capable of surviving the stringent engine load and temperature environment.

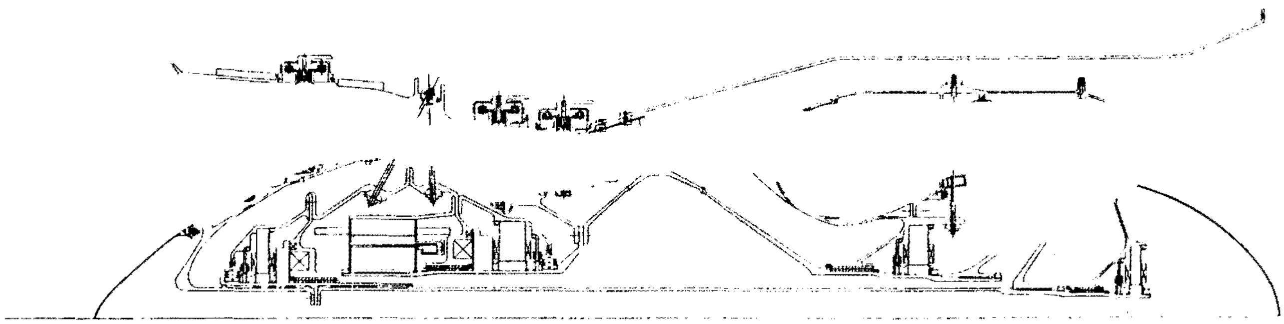

Figure 5. All-Barriers-Removed Magnetic Bearing Engine Design

*(2) Magnetic Bearing Power Electronics*

The size and weight of present, commercially available electronic power amplifiers for magnetic bearings are unsuitable for use in advanced aircraft engines. To fully utilize the superior capabilities of an active magnetic bearing system as compared to the rolling element bearings, power amplifier package weight and volume must be reduced by at least an order of magnitude. No commercially available power amplifier can presently operate in the 640°F ambient and 20 G vibration environment required for the targeted engine application. Lightweight, high power density, fault tolerant power electronics with sufficient gain and bandwidth to meet the acceleration rates commensurate with high shaft speeds and engine G loads must be developed. It must be engine mounted and be capable of surviving the high load and temperature environment.

*(3) High Strength, High Flux Magnetic Materials*

Advanced aircraft engines will require bearings to operate above 3.0 million DN and to require minimum space. Active magnetic bearings have the potential to exceed these requirements. Active magnetic bearings for advanced engine applications require magnetic materials with high saturation flux densities to provide the highest performance while occupying minimum space. Additionally, the rotor lamination magnetic materials must have mechanical yield strengths between 30,000 and 70,000 psi for DN values between 3 and 5 million mm–rpm. Therefore, there is a need to develop heat treatment procedures to produce rotor magnetic materials with yield strengths of 70,000 psi and higher and magnetic saturation flux densities of 2.0 teslas and higher. High mechanical strength, high saturation flux magnetic materials (i.e., Vanadium Permendur and Vanadium Permendur/Nickel) must be optimized to maximize these properties and minimize alternating current losses. Heat treatment procedures need to be developed to provide consistent quality material which meets the required specifications.

*(4) High Temperature Winding Insulation*

Electrical windings for magnetic bearings require impregnation systems for supplementary electrical insulation, mechanical support against vibrations and chemical protection. For engine temperatures (550°F to 1500°F), ceramic impregnation appears to be a promising candidate. High temperature (up to 1500°F) insulation materials for the bearing electrical windings, capable of withstanding a vibratory and changing thermal environment without degrading, are required for magnetic bearing engines.

*(5) Improved Rotor Position Sensors*

A key magnetic bearing component requiring reexamination is the position sensor used as the feedback element. The concept and the design of the position sensor used in magnetic bearing controls need to be reexamined in the light of the unique requirements for the advanced engines and in light of new understanding on the requirements for magnetic bearing sensors. Present commercially available sensors for magnetic bearings were designed for ground–based applications with minimal space restrictions but with major limitations on cost. For the aircraft engine applications, the size of the sensors needs to be reduced significantly because the radial bearing sensor represents about 20 percent of the bearing/sensor length. Thus, there is a need for sensor size reduction without sacrifices in reliability or accuracy. The proof of the new design concept verification of the sensor designs would also be required under the severe conditions imposed by advanced engine applications. Additionally, the availability of extensive control capabilities through digital controls and adaptive control methodologies calls for a re–thinking of sensor concepts and possibly a replacement of the sensor feedback with electronically synthesized feedback signals. The development of new or improved position or velocity sensors with significant improvements in accuracy and capable of operating in the high speed, high temperature engine environment is necessary. They must be space efficient and potentially capable of measuring relative rotor position at the center of the bearing applied force.

*(6) Integral Electric Starter/Generator*

This study has produced size, weight, and power requirements for an advanced engine generator. The generator was mounted on the high speed engine rotor with the overall size envelope being 11–inch OD, 4.8–inch ID, and 6–inch length. The power requirements were 247 KVA continuous (including 40 KVA isolated windings for engine functions), 371 KVA 5–minute rating, and a 467 KVA 10–second rating. Additionally, the minimum ambient air temperature for the subject aircraft was projected to be about 640°F which is quite stringent as compared to currently available generator winding temperature capabilities. Existing aircraft electric power generators utilize a wound rotor design with rotating rectifiers. Because these rectifiers cannot be used in the 640°F environment anticipated for the targeted engine application, and rotor cooling below this temperature is not feasible, new generator technology must be developed. In addition to providing electric power for aircraft services and dual, fully capable isolated windings for engine requirements, the generator will be operated as an electric motor and used to start the engine. If the full potential of active magnetic bearings is to be realized, a main shaft starter/generator must replace the engine tower shaft, gearbox, and associated mechanical drive systems. Improvement on existing high speed motor and generator technology to meet the engine/aircraft needs and to operate reliably in the high temperature engine environment is necessary.

*(7) Auxiliary Support Bearings*

Advanced fail-safe auxiliary bearing technology has been identified as a critical need. In an aircraft engine configuration wherein the primary support for the main shaft rotor is provided by an active magnetic bearing system, the auxiliary bearings would serve as a fail-safe support mechanism. The unlevitated rotor will be statically supported by the auxiliary bearings. In the event of a power failure in the magnetic bearing control circuit or during excessive bearing loading caused by the accidental loss of a turbine blade or severe aircraft maneuvers, the auxiliary bearings must be capable of withstanding these high loads to prevent contact between the magnetic bearing rotor and stator. The auxiliary bearings, under these high loading conditions, must have sufficient life to enable the pilot to fly the aircraft safely to the nearest airbase. Auxiliary bearings must also be capable of withstanding magnetic bearing overloads for a limited time period in the high temperature bearing compartment. Silicon nitride ball bearings (steel races) have shown promise at very high DN levels but at room temperature. The development of non-liquid lubricated sleeve bearings could significantly reduce the high weight associated with the rolling element bearing design.

## PARAMETRIC ANALYSIS

The IHPTET engine designed with all-barriers-removed magnetic bearings formed the basis for studies which ascertained the benefits for an advanced military aircraft engine. Parametric analyses were conducted using state-of-the-art design/analysis tools. The parametric analyses showed that the incorporation of magnetic bearings into a far-term IHPTET military engine could provide a 16% engine weight savings when compared with a current technology IHPTET base type conventional bearing engine. This more-electric engine would be oil free and have an integrated full authority digital electronic control and magnetic bearing control system. This weight savings could provide improvements in aircraft takeoff gross weight (TOGW) and mission range. A 5.6% weight savings was calculated in comparison with a far-term engine with high temperature, liquid lubricated conventional mount rolling element bearings and many of the other projected "electric" engine improvements. This weight savings is considered to be a very high payoff for advanced engine technology for IHPTET.

The incorporation of magnetic bearings into a far-term military engine would provide other major benefits which are known to be positive, but are difficult to quantify. These include reliability, durability, maintainability, vibration control, fire safety, reduced heat rejection, and cost. The improvements in reliability, durability, and vibration control are exemplified by the dramatic change in the engine external components relative to a conventional engine of today. The incorporation of magnetic bearings and other associated more-electric components would produce an engine with significantly less plumbing and mechanical structure which is susceptible to vibration fatigue failure. The elimination of a majority of the failure-prone hardware alone will provide a greater than 2:1 improvement in reliability. With the anticipated superior vibration control of magnetic bearings, the durability of the remaining structure (e.g., fuel and air lines) would be significantly improved. Improvements in maintainability of the engine external structure is readily apparent primarily because of simplicity. Remaining components only include the full electronic control system, electric fuel pump and associated delivery systems, electric actuators, and the air bleed and service systems.

The elimination of oil and hydraulic fluids would greatly improve the fire safety of the aircraft. The total impact of this benefit has not been assessed. Heat generation within the bearing and power section of the control system has also not been assessed in detail, but in comparison with rolling element bearings, reductions of more than 5:1 are expected. This is particularly important for high Mach number aircraft which utilize fuel/oil coolers and air/oil heat exchangers at the expense of range and fuel burn. The issue of system cost was not addressed in this study, but if the historical trends in changeovers from mechanical to electronic systems are an indication, lower cost is anticipated.

Within the scope of this program, the search for penalties associated with the implementation of magnetic bearings into an advanced military engine did not surface anything significant. A magnetic bearing engine would be dramatically different than today's engines, and before full-scale engine development can be initiated, technology shortfalls must be addressed to achieve technology readiness within the IHPTET time frame. Much of this development represents a maturing of known technology and does not require significant breakthroughs. However, technology development must be pursued to reduce the risk to a level commensurate with the time frame associated with 21st century engine development. The payoff potential of magnetic bearing engines is significant and achievable.

## CONCLUSIONS

Active magnetic bearings as replacements for conventional oil lubricated rolling element bearings in advanced military aircraft engines is feasible for 21st century applications. The engine feasibility study described herein provided invaluable insight into active magnetic bearings for advanced military engines. It is concluded that the application is practical and the required technologies could be matured to achieve technology readiness by the turn of the century. Many benefits have been defined and, in particular, have shown that significant weight savings are possible, increased reliability and durability are achievable, and higher levels of overall engine performance could result. The successful application of this concept would result in engines with no lubrication system, higher rotor speeds, reduced blade tip and seal clearances, reduced cooling and thrust balance air, reduced system weight, and enhanced rotor dynamic control. These features would, in turn, enhance propulsion system fuel consumption, thrust-to-weight ratio, maintenance, and reliability, thus providing greater aircraft capability with lower life cycle cost.

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