United States Patent	12392307
Kind Code	B2
Date of Patent	August 19, 2025
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High-speed shaft rating for turbine engines

Abstract

A turbomachine engine includes an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine. The engine core has a length (L.sub.CORE), and the high-pressure compressor has an exit stage diameter (D.sub.CORE). A high-pressure shaft is coupled to the high-pressure compressor and the high-pressure turbine. The high-pressure shaft is characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and a ratio of L.sub.CORE/D.sub.CORE is from 2.1 to 4.3.

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Appl. No.: **18/330155**

Filed: **June 06, 2023**

Prior Publication Data

Document Identifier	Publication Date
US 20240318614 A1	Sep. 26, 2024

Foreign Application Priority Data

IN	202311020971	Mar. 24, 2023

Publication Classification

Int. Cl.: **F02K3/075** (20060101); **F02C3/06** (20060101)

U.S. Cl.:

CPC **F02K3/075** (20130101); **F02C3/06** (20130101);

Field of Classification Search

CPC: F02K (3/075); F02C (3/06)

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Background/Summary

CROSS REFERENCE TO RELATED APPLICATIONS
(1) The present application claims the benefit of Indian Patent Application No. 202311020971, filed on Mar. 24, 2023, which is hereby incorporated by reference herein in its entirety.
TECHNICAL FIELD
(2) The present disclosure relates generally to engine cores for turbine engines.
BACKGROUND
(3) A turbofan engine, or turbomachinery engine, includes one or more compressors, and a power turbine (also referred to as a low-pressure turbine) that drives a bypass fan. The bypass fan is coupled to the power turbine via a turbomachine shaft. The turbomachinery engine also includes an engine core comprising a high-pressure compressor, a combustor, and a high-pressure turbine. The high-pressure compressor is coupled to the high-pressure turbine via a high-pressure shaft.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The foregoing and other features and advantages will be apparent from the following, more particular, description of various exemplary embodiments, as illustrated in the accompanying drawings, wherein like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements.
(2) FIG. **1** is a schematic, cross-sectional diagram of a turbine engine, taken along a longitudinal centerline axis of the turbine engine, according to the present disclosure.
(3) FIG. **2** is a schematic, cross-sectional diagram of a turbine engine, taken along a longitudinal centerline axis of the turbine engine, according to another embodiment of the present disclosure.
(4) FIG. **3** is a schematic, cross-sectional view of a ducted, indirect-drive, turbine engine, taken along a longitudinal centerline axis of the turbine engine, according to an embodiment of the present disclosure.
(5) FIG. **4** is a schematic view of an unducted, three-stream, turbine engine for an aircraft, taken along a longitudinal centerline axis of the turbine engine, according to an embodiment of the present disclosure.
(6) FIG. **5** is a cross-sectional view of an exemplary turbine engine, taken along a longitudinal centerline axis of the turbine engine, according to the present disclosure.
(7) FIG. **6** is an enlarged, schematic view of the turbine engine of FIG. **5**, taken at detail **601** in FIG. **5**, according to the present disclosure.
(8) FIG. **7**A shows a first bending mode of a shaft.
(9) FIG. **7**B shows a second bending mode of a shaft.
(10) FIG. **7**C shows a third bending mode of a shaft.
(11) FIG. **8** represents, in graph form, a range of a high-speed shaft rating (HSR). In particular, FIG. **8** depicts a ratio of the length of the engine core to the diameter of the engine core

(L.sub.CORE/D.sub.CORE) as a function of a first high-speed shaft operating parameter (HSP.sub.X) given by relationship (5) detailed below.
(12) FIG. **9** represents, in graph form, a range of a high-speed shaft rating (HSR), according to another embodiment.
(13) FIG. **10** represents, in graph form, an area ratio high-speed shaft rating (HSP.sub.AR) as a function of the HSP.sub.X.
(14) FIG. **11** represents, in graph form, an area ratio high-speed shaft rating (HSP.sub.AR) as a function of the HSP.sub.X, according to another embodiment.
(15) FIG. **12** represents, in graph form, an inlet area high-speed shaft rating (HSP_A.sub.IN) as a function of a second high-speed shaft operating parameter (HSP.sub.X1) as given by relationship (12) detailed below.
(16) FIG. **13** represents, in graph form, an exit rim speed (at redline speeds) high-speed shaft rating (HSP_U.sub.RIM,R/L) as a function of the HSP.sub.X.
(17) FIG. **14** represents, in graph form, an exit rim speed (at redline speeds) high-speed shaft rating (HSP_U.sub.RIM,R/L) as a function of the HSP.sub.X, according to another embodiment.
(18) FIG. **15** represents, in graph form, a HP compressor tip radius ratio high-speed shaft rating (HSP.sub.RR) as a function of the HSP.sub.X.
(19) FIG. **16** represents, in graph form, a HP compressor tip radius ratio high-speed shaft rating (HSP.sub.RR) as a function of the HSP.sub.X, according to another embodiment.

DETAILED DESCRIPTION

(20) Additional features, advantages, and embodiments of the present disclosure are set forth or apparent from a consideration of the following detailed description, drawings, and claims. Moreover, both the foregoing summary of the present disclosure and the following detailed description are exemplary and intended to provide further explanation without limiting the scope of the disclosure as claimed.
(21) Various embodiments of the present disclosure are discussed in detail below. While specific embodiments are discussed, this is done for illustration purposes only. A person skilled in the relevant art will recognize that other components and configurations may be used without departing from the spirit and the scope of the present disclosure.
(22) As used herein, the terms “first,” “second,” “third,” and “fourth” may be used interchangeably to distinguish one component from another and are not intended to signify location or importance of the individual components.
(23) The terms “forward” and “aft” refer to relative positions within a turbine engine or vehicle, and refer to the normal operational attitude of the turbine engine or vehicle. For example, with regard to a turbine engine, forward refers to a position closer to an engine inlet and aft refers to a position closer to an engine nozzle or exhaust.
(24) The terms “upstream” and “downstream” refer to the relative direction with respect to fluid flow in a fluid pathway. For example, “upstream” refers to the direction from which the fluid flows, and “downstream” refers to the direction to which the fluid flows.
(25) The terms “low” and “high,” or their respective comparative degrees (e.g., “lower” and “higher,” where applicable), when used with the compressor, turbine, shaft, or spool components, each refers to relative pressures and/or relative speeds within an engine unless otherwise specified. For example, a “low-speed” component defines a component configured to operate at a rotational speed, such as a maximum allowable rotational speed, which is lower than that of a “high-speed” component of the engine. Alternatively, unless otherwise specified, the aforementioned terms may be understood in their superlative degree. For example, a “low-pressure turbine” may refer to the lowest maximum pressure within a turbine section, and a “high-pressure turbine” may refer to the highest maximum pressure within the turbine section. The terms “low” or “high” in such aforementioned regards may additionally, or alternatively, be understood as relative to minimum allowable speeds and/or pressures, or minimum or maximum allowable speeds and/or pressures

relative to normal, desired, steady state, etc., operation of the engine.
(26) The terms “coupled,” “fixed,” “attached,” “connected,” and the like, refer to both direct coupling, fixing, attaching, or connecting, as well as indirect coupling, fixing, attaching, or connecting through one or more intermediate components or features, unless otherwise specified herein.
(27) The singular forms “a,” “an,” and “the” include plural references unless the context clearly dictates otherwise.
(28) As used herein, the terms “axial” and “axially” refer to directions and orientations that extend substantially parallel to a longitudinal centerline of the turbine engine. Moreover, the terms “radial” and “radially” refer to directions and orientations that extend substantially perpendicular to the longitudinal centerline of the turbine engine. In addition, as used herein, the terms “circumferential” and “circumferentially” refers to directions and orientations that extend arcuately about the longitudinal centerline of the turbine engine.
(29) As used herein, “overall pressure ratio (OPR)” of a compressor is a ratio of the pressure at the exit of the compressor to the pressure at the inlet of the compressor.
(30) As used herein, “redline speed” means the maximum expected rotational speed of a shaft during normal operation of an engine. The redline speed may be expressed in terms of rotations per second in Hertz (Hz), rotations per minute (RPM), or as a linear velocity of the outer diameter of the shaft in terms of feet per second. For a gas turbine engine that has a high-speed shaft and a low-speed shaft, both the high-speed shaft and the low-speed shaft have redline speeds, The redline speeds of the shafts are typically reported in an engine Type Certificate Data Sheet (TCDS). Alternatively, redline speeds can be referred to as maximum permissible shaft speed at take-off flight conditions (e.g., over a 5 minute duration).
(31) As used herein, “critical speed” means a rotational speed of the shaft that is about the same as the fundamental, or natural frequency of a first-order bending mode of the shaft (e.g., the shaft rotates at eighty Hz and the first-order modal frequency is eighty Hertz). When the shaft rotates at the critical speed, the shaft is expected to have a maximum amount of deflection, hence, instability, due to excitation of the first-order bending mode of the shaft. The critical speed may be expressed in terms of rotations per second in Hertz (Hz), rotations per minute (RPM), or as a linear velocity of the outer diameter of the shaft in terms of feet per second.
(32) As used herein, “critical frequency” and “fundamental frequency” are referred to interchangeably and refer to the fundamental, or natural frequency, of the first-order bending mode of the shaft.
(33) The term “subcritical speed” refers to a shaft redline speed that is less than the fundamental, or natural frequency of the first-order bending mode of the shaft (e.g., the shaft rotates at a redline speed of 70 Hz while the first-order modal frequency is about 80 Hertz). When the rotational speed is subcritical, the shaft is more stable than when rotating at a critical speed. A “subcritical shaft” is a shaft that has a redline speed below the critical speed of the shaft.
(34) The term “supercritical speed” refers to a shaft rotational speed that is above the fundamental, or natural frequency of the first-order bending mode of the shaft (e.g., the shaft rotates at eighty Hz while the first-order modal frequency is about seventy Hertz). A supercritical shaft is less stable than a subcritical shaft because the shaft speed can pass through the critical speed since the fundamental mode of the shaft is below the redline speed. A “supercritical shaft” is a shaft that has a redline speed above the critical speed of the shaft.
(35) As used herein, “bypass ratio” is a ratio between the mass flow rate of air drawn through the fan that goes around the core engine (e.g., the turbomachine) to the mass flow rate of the air that enters the core engine. In other words, the bypass ratio is the ratio of air that bypasses the core engine to the air that passes into the core engine.
(36) As used herein, the term “ceramic matrix composite” (“CMC”) refers to a subgroup of composite materials and a subgroup of ceramics. The terms “CMC” and “CMC material” are used

interchangeably herein. When the engine component (e.g., the higher pressure turbine module, nozzle, or blades thereof) comprises or includes "CMC" or "CMC material," the engine component may include one of, or combinations of one or more of the ceramic matrix composite materials described herein. Such engine component may also include non-ceramic matrix composite materials, such as a metal alloy (e.g., a CMC material for an airfoil and a separate disk with a dovetail slot made from a metal alloy). Reference to a "first" or a "second" or a "third" CMC material does not preclude the materials from including multiple CMC materials, different CMC materials, or the same CMC materials.

(37) More specifically, CMC refers to a class of materials that includes a reinforcing material (e.g., reinforcing fibers) surrounded by a ceramic matrix phase. Generally, the reinforcing fibers provide structural integrity to the ceramic matrix. Some examples of matrix materials of CMCs can include, but are not limited to, non-oxide silicon-based materials (e.g., silicon carbide, silicon nitride, or mixtures thereof), oxide ceramics (e.g., silicon oxycarbides, silicon oxynitrides, aluminum oxide (Al.sub.2O.sub.3), silicon dioxide (SiO.sub.2), aluminosilicates, or mixtures thereof), or mixtures thereof. Optionally, ceramic particles (e.g., oxides of Si, Al, Zr, Y, and combinations thereof) and inorganic fillers (e.g., pyrophyllite, wollastonite, mica, talc, kyanite, and montmorillonite) may also be included within the CMC matrix.

(38) Some examples of reinforcing fibers of CMCs can include, but are not limited to, non-oxide silicon-based materials (e.g., silicon carbide, silicon nitride, or mixtures thereof), non-oxide carbon-based materials (e.g., carbon), oxide ceramics (e.g., silicon oxycarbides, silicon oxynitrides, aluminum oxide (Al.sub.2O.sub.3), silicon dioxide (SiO.sub.2), aluminosilicates such as mullite, or mixtures thereof), or mixtures thereof.

(39) Generally, particular CMCs may be referred to as their combination of type of fiber/type of matrix. For example, C/SiC for carbon-fiber-reinforced silicon carbide, SiC/SiC for silicon carbide-fiber-reinforced silicon carbide, SiC/SiN for silicon carbide fiber-reinforced silicon nitride, SiC/SiC—SiN for silicon carbide fiber-reinforced silicon carbide/silicon nitride matrix mixture, etc. In other examples, the CMCs may include a matrix and reinforcing fibers comprising oxide-based materials such as aluminum oxide (Al.sub.2O.sub.3), silicon dioxide (SiO.sub.2), aluminosilicates, and mixtures thereof. Aluminosilicates can include crystalline materials such as mullite (3Al.sub.2O.sub.3.Math.2SiO.sub.2), as well as glassy aluminosilicates.

(40) In certain embodiments, the reinforcing fibers may be bundled and/or coated prior to inclusion within the matrix. For example, bundles of the fibers may be formed as a reinforced tape, such as a unidirectional reinforced tape. A plurality of the tapes may be laid up together to form a preform component. The bundles of fibers may be impregnated with a slurry composition prior to forming the preform or after formation of the preform. The preform may then undergo thermal processing and subsequent chemical processing to arrive at a component formed of a CMC material having a desired chemical composition. For example, the preform may undergo a cure or burn-out to yield a high char residue in the preform, and subsequent melt-infiltration ("MI") with silicon, or a cure or pyrolysis to yield a silicon carbide matrix in the preform, and subsequent chemical vapor infiltration ("CVI") with silicon carbide. Additional steps may be taken to improve densification of the preform, either before or after chemical vapor infiltration, by injecting the preform with a liquid resin or polymer followed by a thermal processing step to fill the voids with silicon carbide. CMC material as used herein may be formed using any known methods or hereafter developed including but not limited to melt infiltration, chemical vapor infiltration, polymer impregnation pyrolysis (PIP) and any combination thereof.

(41) Such materials, along with certain monolithic ceramics (i.e., ceramic materials without a reinforcing material), are particularly suitable for higher temperature applications. Additionally, these ceramic materials are lightweight compared to metal alloys (e.g., superalloys), yet can still provide strength and durability to the component made therefrom. Therefore, such materials are currently being considered for many gas turbine components used in higher temperature sections of

gas turbine engines, such as airfoils (e.g., turbines, and vanes), combustors, shrouds and other like components, that would benefit from the lighter-weight and higher temperature capability these materials can offer.

(42) Here and throughout the specification and claims, range limitations are combined, and interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise. For example, all ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other.

(43) One or more components of the turbomachine engine described herein below may be manufactured or formed using any suitable process, such as an additive manufacturing process, such as a three-dimensional (3D) printing process. The use of such a process may allow such a component to be formed integrally, as a single monolithic component, or as any suitable number of sub-components. In particular, the additive manufacturing process may allow such a component to be integrally formed and include a variety of features not possible when using prior manufacturing methods. For example, the additive manufacturing methods described herein enable the manufacture of shafts having unique features, configurations, thicknesses, materials, densities, passageways, headers, and mounting structures that may not have been possible or practical using prior manufacturing methods. Some of these features are described herein.

(44) This disclosure and various embodiments relate to a turbomachinery engine, also referred to as a turbine engine, a gas turbine engine, a turboprop engine, or a turbomachine. These turbomachinery engines can be applied across various technologies and industries. Various embodiments may be described herein in the context of aeronautical engines and aircraft machinery.

(45) In some instances, a turbomachinery engine is configured as a direct drive engine. In other instances, a turbomachinery engine can be configured as an indirect drive engine with a gearbox. In some instances, a propulsor of a turbomachinery engine can be a fan encased within a fan case and/or a nacelle. This type of turbomachinery engine can be referred to as “a ducted engine.” In other instances, a propulsor of a turbomachinery engine can be exposed (e.g., not within a fan case or a nacelle). This type of turbomachinery engine can be referred to as “an open rotor engine” or an “unducted engine,” and includes, but is not limited to, ducted variable pitch fan configuration, counter rotating turbine/compressor configurations with a plurality of LP shafts connecting the compressors and the fan to the respective turbines and the engine core concentrically enveloping the plurality of LP shafts, and/or configurations with a reverse core in which the LP shafts do not concentrically pass through engine core.

(46) A turbofan engine, or turbomachinery engine, includes a core engine and a power turbine that drives a bypass fan. The bypass fan generates the majority of the thrust of the turbofan engine. The generated thrust can be used to move a payload (e.g., an aircraft). A turbomachine shaft coupled to the power turbine and fan (either directly or through a gearbox) can experience vibrations during operation of the engine. For example, when the shaft rotates at the critical speed of the shaft, the shaft will vibrate excessively. The excessive vibration is due primarily to excitation of a first-order beam bending mode of the shaft. Thus, the shaft may be characterized by a first-order beam bending mode of the shaft, the fundamental resonance frequency (fundamental frequency) of this mode, and the critical speed of rotation of the shaft. If the first-order bending mode may be excited by a low-speed shaft rate occurring during a standard operating range of the engine, undetected vibration, as well as an increased risk of whirl instability, may result.

(47) Newer engine architectures may be characterized by higher bypass ratio (e.g., greater than 8.0, greater than 10.0, or greater than 12.0) engine designs to improve overall efficiency of the engine in converting kinetic energy to mechanical energy in the form of propulsion. For example, the bypass ratio is greater than 8.0 for engine thrust class of less than 20,000 lbf, greater than 10.0 for engine thrust class of about 20,000 lbf, and greater than 12.0 for engine thrust class of greater than 30,000 lbf. Typically, the fan size is increased to achieve the higher bypass ratios and the low-

pressure (LP) shaft that couples the LP turbine and the LP compressor is also increased to accommodate the larger fan sizes. The increase in the LP shaft, however, results in lower shaft speeds and lower overall power through the LP shaft to the fan. Additionally, the engine core (e.g., the high-pressure compressor, the combustor, and the high-pressure turbine) needs to fit within a smaller space as the bypass ratios are increased. These trends can result in reductions in stiffness-to-weight ratio for the shaft and structure that influences dynamics of the HP shaft. For example, with the higher bypass ratio engines, the flow size (e.g., mass flow rate) to the engine core decreases. Typically, the size (e.g., length and diameter) of the HP shaft is scaled down to accommodate the decreased flow size in order to decrease the overall size of the engine core (e.g., smaller engine core). However, components of the engine core (e.g., the blades, the vanes or the nozzles, the axial gaps between the blades and the vanes or the nozzles and/or the combustor) are unable to be scaled down to achieve the smaller engine core while maintaining the desired thrust for a particular engine thrust class.

(48) The length of the engine core and the diameter of the engine core each affect the dynamics of the HP shaft. For example, the HP shaft dynamics is dependent on the engine core length to diameter ratio (L.sub.CORE/D.sub.CORE). Higher L.sub.CORE/D.sub.CORE values result in reduced margins for Alford stability (e.g., a fundamental/first bending mode that is an excitation due to clearance changes around the periphery of the HP rotor) and for the third mode (e.g., an S-shaped bending mode that occurs at redline speeds) of the HP shaft. In particular, as the L.sub.CORE/D.sub.CORE value increases, the Alford margin and the third mode margin decreases, thereby, lowering the maximum allowable redline speeds at which the HP shaft may rotate before experiencing instability due to Alford forces and/or excessive excitation of the third mode.

(49) Typically, the decreased Alford margin and the third mode margin are mitigated by increasing the radius ratio (e.g., a ratio of the hub radius to the tip radius) of the HP compressor (e.g., increasing diameter of the HP compressor) and reducing the HP compressor stage count (e.g., resulting in a reduced engine core length). However, this results in poorer aerodynamic performance of the HP compressor and/or of the HP turbine (e.g., higher tip clearance to blade height ratios), increased weight of the engine core (e.g., and of the overall engine), and a reduced overall pressure ratio (OPR) due to lower pressure ratio from the HP compressor. To enable higher OPRs, the pressure ratio is transferred to a booster (e.g., low-pressure compressor), resulting in increased HP compressor inlet temperatures (e.g., also referred to as T25). This causes higher HP shaft redline speeds (e.g., for similar inlet corrected flow conditions), thereby decreasing the Alford margin and the third mode margin. Increasing the HP shaft length also increases the LP shaft length to accommodate the longer HP shaft. Further, the higher HP shaft redline speed and the smaller engine core diameter restricts the LP shaft diameter (e.g., reduced core bearing diameters due to DN limits (e.g., DN is the product of diameter (D) in mm and speed (N) in RPM and is used to determine the correct lubricant viscosity for a particular bearing), reduced HP disk bore diameters, etc.), thereby limiting the design space for subcritical shaft designs or a feasible diameter for the LP shaft to support the required torque. For example, as the shaft speeds increase, the bearings that support the HP shaft have to be decreased in diameter to accommodate the faster shaft speeds and smaller core size. This puts a constraint on the diameter of the LP shaft, thereby affecting the dynamics of the LP shaft.

(50) Thus, a balance is ultimately struck (penalties vs. benefits) to maintain or to enhance engine performance (e.g., by increasing the bypass ratio), while also enabling an increase in the redline speed of the HP shaft, or not lowering the critical speed, e.g., add one or two additional stages to a compressor to increase efficiency, to allow for smaller engine cores and higher bypass ratio engines without operating at instabilities due to Alford forces or the third bending mode of the HP shaft.

(51) As part of this effort, the inventors evaluated the influence of changes in size of the core, and resulting impact that these modifications have on the dynamics of the high-speed shaft, the low-speed shaft, and the interaction between these two shafts as can occur through dynamic excitation

transmitted through shaft bearings. Thus, the inventors, as part of their investigation and evaluation of different engine architectures, considered how the dynamics of the HP shaft might change when the engine core changes in size and weight, in response to a need to operate at higher bypass ratios.
(52) Different approaches for engine types, midshaft geometry, bearing support, and material compositions are needed for next-generation turbomachine engines, to permit high-speed operation without resulting in an unstable bending mode and Alford stability, and, therefore, vibrations during regular operation. The inventors, tasked with finding a suitable design to meet these requirements while lowering vibrations, or at least maintaining a tolerable vibration environment during flight conditions (e.g., takeoff or max thrust), conceived of and tested a wide variety of shafts and HP compressor geometries having different combinations of HP inlet temperature, HP pressure ratio, shaft length, shaft diameter, HP compressor inlet size, and HP compressor exit size in order to determine which embodiment(s) were most promising for a variety of contemplated engine designs, including different engine core sizes for different sized high-pressure compressors and high-pressure turbines. The various embodiments, as described herein including illustrated examples for both a ducted fan configuration and an open fan configuration of a gas turbine engine, include turbomachine shafts that employ one or more of the above-mentioned techniques to increase the maximum allowable redline speed of the HP shaft and/or to maintain a design speed for improved efficiency while mitigating or avoiding instability due to Alford forces and/or excessive excitation of the HP shaft third mode.
(53) Referring now to the drawings, FIG. **1** is a schematic cross-sectional diagram of a turbine engine **100**, taken along a longitudinal centerline axis **101** of the turbine engine **100**, according to an embodiment of the present disclosure. For the embodiment depicted in FIG. **1**, the turbine engine **100** is a high bypass ratio turbofan engine. The turbine engine **100** has an axial direction A (extending parallel to the longitudinal centerline axis **101** provided for reference) and a radial direction R that is normal to the axial direction A. In general, the turbine engine **100** includes a fan section **102** and a turbomachine **104** disposed downstream from the fan section **102**. The terms “gas turbine engine,” “turbomachine engine,” “turbomachinery engine,” and “turbine engine” are used interchangeably herein.
(54) The turbomachine **104** depicted generally includes an outer casing **106** that is substantially tubular and defines an inlet **108**. In this embodiment, the inlet **108** is annular. As schematically shown in FIG. **1**, the outer casing **106** encases, in serial flow relationship, a compressor section **105** including a booster or a low-pressure (LP) compressor **110** followed downstream by a high-pressure (HP) compressor **112**, a combustion section **114**, a turbine section **107** including a high-pressure (HP) turbine **116** followed downstream by a low-pressure (LP) turbine **118**, and a jet exhaust nozzle section **120**. The LP turbine **118** is also referred to as a power turbine. The compressor section **105**, the combustion section **114**, the turbine section **107**, and the jet exhaust nozzle section **120** together define a core air flowpath **121**. A high-pressure (HP) shaft **122** (also referred to as a high-speed shaft) drivingly connects the HP turbine **116** to the HP compressor **112** to rotate the HP turbine **116** and the HP compressor **112** in unison. Together, the HP compressor **112**, the combustion section **114**, and the HP turbine **116** define an engine core **123** of the turbine engine **100**. A low-pressure (LP) shaft **124** (also referred to as a low-speed shaft) drivingly connects the LP turbine **118** to the LP compressor **110** to rotate the LP turbine **118** and the LP compressor **110** in unison. In this way, the turbine engine **100** is a two-spool gas turbine engine.
(55) In some embodiments, the turbine engine **100** includes an intercooler **109**. The intercooler **109** cools the engine flow path air downstream of the LP compressor **110** before the engine flow path air enters the HP compressor **112** during flight conditions (e.g., takeoff or maximum thrust). The intercooler **109** can include any type of intercooler. For example, the intercooler **109** can include a heat exchanger in the inter-compressor frame or inter-compressor casing (e.g., in the outer casing **106**) in which cooling fluid is used to absorb heat with the flow path air. The cooling fluid can include a thermal bus or fuel. The thermal bus can absorb heat from the core air and reject the heat

into a heat sink, such as, for example, fuel and/or bypass air. In some embodiments, the intercooler **109** can include a heat exchanger between the core air and the bypass air. In some embodiments, the intercooler **109** includes water or steam that is injected into the core flow path at the inter-compressor frame. While the intercooler **109** is described in relation to FIG. **1**, any of the turbine engines detailed herein can include an intercooler **109**.

(56) For the embodiment depicted in FIG. **1**, the fan section **102** includes a fan **126** having a plurality of fan blades **128** coupled to a disk **130** in a spaced apart manner. As depicted in FIG. **1**, the fan blades **128** extend outwardly from the disk **130** generally along the radial direction R. In some embodiments, each fan blade **128** is rotatable relative to the disk **130** about a pitch axis such that the pitch of the plurality of fan blades **128** can be collectively varied in unison. The plurality of fan blades **128** and the disk **130** are together rotatable about the longitudinal centerline axis **101** by the LP shaft **124**. In this way, the turbine engine **100** is considered a direct drive turbine engine. The disk **130** is covered by a rotatable fan hub **132** aerodynamically contoured to promote an airflow through the plurality of fan blades **128**. In addition, the fan section **102** includes an annular fan casing or a nacelle **134** that circumferentially surrounds the fan **126** and/or at least a portion of the turbomachine **104**. The nacelle **134** is supported relative to the turbomachine **104** by a plurality of circumferentially spaced outlet guide vanes **136**. Moreover, a downstream section **138** of the nacelle **134** extends over an outer portion of the turbomachine **104** to define a bypass airflow passage **140** therebetween. In this way, the turbine engine **100** is considered a ducted fan engine.

(57) During operation of the turbine engine **100**, a volume of air **150** enters the turbine engine **100** through an inlet **152** of the nacelle **134** and/or the fan section **102**. As the volume of air **150** passes across the plurality of fan blades **128**, a first portion of air **154** is directed or routed into the bypass airflow passage **140**, and a second portion of air **156** is directed or is routed into the upstream section of the core air flowpath **121**, or, more specifically, into the inlet **108** of the LP compressor **110**. The ratio between the first portion of air **154** and the second portion of air **156** is commonly known as a bypass ratio. The turbine engine **100** has a high bypass ratio (e.g., greater than 8.0, greater than 10.0, or greater than 12.0), as detailed further below. The pressure of the second portion of air **156** is then increased, forming compressed air **158**, and the compressed air **158** is routed through the HP compressor **112** and into the combustion section **114**, where the compressed air **158** is mixed with fuel and burned to provide combustion gases **160**.

(58) The combustion gases **160** are routed into the HP turbine **116** and expanded through the HP turbine **116** where a portion of thermal and/or of kinetic energy from the combustion gases **160** is extracted via sequential stages of HP turbine stator vanes **162** that are coupled to the outer casing **106** and HP turbine rotor blades **164** that are coupled to the HP shaft **122**, thus, causing the HP shaft **122** to rotate, thereby supporting operation of the HP compressor **112**. The combustion gases **160** are then routed into the LP turbine **118** and expanded through the LP turbine **118**. Here, a second portion of thermal and kinetic energy is extracted from the combustion gases **160** via sequential stages of LP turbine stator vanes **166** that are coupled to the outer casing **106** and LP turbine rotor blades **168** that are coupled to the LP shaft **124**, thus, causing the LP shaft **124** to rotate, thereby supporting operation of the LP compressor **110** and rotation of the fan **126** via LP shaft **124**.

(59) The combustion gases **160** are subsequently routed through the jet exhaust nozzle section **120** of the turbomachine **104** to provide propulsive thrust. Simultaneously, the pressure of the first portion of air **154** is substantially increased as the first portion of air **154** is routed through the bypass airflow passage **140** before being exhausted from a fan nozzle exhaust section **170** of the turbine engine **100**, also providing propulsive thrust.

(60) The turbine engine **100** depicted in FIG. **1** is by way of example only. In other exemplary embodiments, the turbine engine **100** may have any other suitable configuration. For example, in other embodiments, the engine may be any other suitable gas turbine engine, such as a turboshaft engine, a turboprop engine, a turbojet engine, an unducted single fan engine, and the like. In such a

manner, in other embodiments, the gas turbine engine may have other suitable configurations, such as other suitable numbers or arrangements of shafts, compressors, turbines, fans, etc. Further, although the turbine engine **100** is shown as a direct drive, fixed-pitch turbofan engine, in other embodiments, a turbine engine may be a geared gas turbine engine (i.e., including a gearbox between the fan **126** and shaft driving the fan, such as the LP shaft **124**), may be a variable pitch gas turbine engine (i.e., including a fan **126** having a plurality of fan blades **128** rotatable about their respective pitch axes), etc. Further, still, in alternative embodiments, the turbine engine **100** can include a counter rotating LP shaft architecture in which two shafts of the turbine engine **100** rotate in opposite directions.

(61) FIG. **2** is a schematic cross-sectional diagram of a turbine engine **210**, taken along a longitudinal centerline axis **212** of the turbine engine **210**, according to an embodiment of the present disclosure. The turbine engine **210** is similar in some respects to the turbine engine **100** discussed above with respect to FIG. **1**. The turbine engine **210**, however, is a three-spool turbine engine, as detailed further below. For the embodiment depicted in FIG. **2**, the turbine engine **210** is a high bypass ratio turbofan engine. The turbine engine **210** has an axial direction A (extending parallel to the longitudinal centerline axis **212** provided for reference) and a radial direction R that is normal to the axial direction A. The turbine engine **210** extends from a forward end **211** to an aft end **213** along the axial direction A. The forward end **211** is upstream of the aft end **213**. In general, the turbine engine **210** includes a fan section **214** and a turbomachine **216** disposed downstream from the fan section **214**.

(62) The turbine engine **210** include a substantially tubular, outer casing **218** that defines an inlet **220**. The inlet **220** is annular. The outer casing **218** encases, in serial flow arrangement, a compressor section **221** including an intermediate-pressure (IP) compressor **222** followed downstream by a high-pressure (HP) compressor **224**, a combustion section **226**, and a turbine section **228** including a high-pressure (HP) turbine **230** followed downstream by an intermediate-pressure (IP) turbine **232**, a low-pressure (LP) turbine **233**, and a jet exhaust nozzle section **237**. The LP turbine **233** is also referred to as a power turbine. A high-pressure (HP) shaft **234** (also referred to as a high-speed shaft) drivingly connects the HP turbine **230** to the HP compressor **224** to rotate the HP turbine **230** and the HP compressor **224** in unison. Together, the HP compressor **224**, the combustion section **226**, and the HP turbine **230** define an engine core **231** of the turbine engine **210**. An intermediate-pressure (IP) shaft **235** (also referred to as an intermediate-speed shaft) drivingly connects the IP turbine **232** to the IP compressor **222** to rotate the IP turbine **232** and the IP compressor **222** in unison. A low-pressure (LP) shaft **236** (also referred to as a low-speed shaft) drivingly connects the LP turbine **233** to the fan section **214** to rotate the LP turbine **233** and the plurality of fan blades **242** in unison. In this way, the turbine engine **210** is a three-spool turbine engine.

(63) The fan section **214** further includes or defines one or more stages of a plurality of fan blades **242** that are coupled to and extend outwardly in the radial direction R from a fan shaft **215** and/or from the LP shaft **236**. The plurality of fan blades **242** are rotatable about the longitudinal centerline axis **212** by the LP shaft **236**. In this way, the turbine engine **210** is considered a direct drive turbine engine. An annular fan casing or a nacelle **244** circumferentially surrounds at least a portion of the fan section **214** and/or at least a portion of the outer casing **218**. The nacelle **244** is supported relative to the outer casing **218** by a plurality of outlet guide vanes **246** that are circumferentially spaced about the outer casing **218**. At least a portion of the nacelle **244** extends over an outer portion (in radial direction R) of the outer casing **218** so as to define a bypass airflow passage **248** therebetween. In this way, the turbine engine **210** is considered a ducted fan engine.

(64) The turbine engine **210** of FIG. **2** operates in a similar manner as the turbine engine **100** of FIG. **1**. During operation of the turbine engine **210**, a volume of air **274** enters the turbine engine **210** through an inlet **276** of the nacelle **244** and/or the fan section **214**. As the volume of air **274** passes across the plurality of fan blades **242**, a first portion of air **278** is directed or routed into the

bypass airflow passage **248**, and a second portion of air **280** is directed or is routed into the upstream section of the turbomachine **216**, or, more specifically, into the inlet **220**. The ratio between the first portion of air **278** and the second portion of air **280** is commonly known as a bypass ratio. The turbine engine **210** has a high bypass ratio (e.g., greater than 8.0, greater than 10.0, or greater than 12.0), as detailed further below. The pressure of the second portion of air **280** is then increased through the IP compressor **222**, forming compressed air **282**, and the compressed air **282** is routed through the HP compressor **224** and into the combustion section **226**, where the compressed air **282** is mixed with fuel and burned to provide combustion gases **284**.

(65) The combustion gases **284** are routed into the HP turbine **230** and expanded through the HP turbine **230** where a portion of thermal and/or of kinetic energy from the combustion gases **284** is extracted via sequential stages of HP turbine stator vanes **286** that are coupled to the outer casing **218** and HP turbine rotor blades **288** that are coupled to the HP shaft **234**, thus, causing the HP shaft **234** to rotate, thereby supporting operation of the HP compressor **224**. The combustion gases **284** are then routed into the IP turbine **232** and expanded through the IP turbine **232**. Here, a second portion of thermal and kinetic energy is extracted from the combustion gases **284** via sequential stages of IP turbine stator vanes **290** that are coupled to the outer casing **218** and IP turbine rotor blades **292** that are coupled to the IP shaft **235**, thus, causing the IP shaft **235** to rotate, thereby supporting operation of the IP compressor **222**. The combustion gases **284** are then routed into the LP turbine **233** and expanded further through the LP turbine **233**. Here, a third portion of thermal and kinetic energy is extracted from the combustion gases **284** via sequential stages of LP turbine stator vanes **294** that are coupled to the outer casing **218** and LP turbine rotor blades **296** that are coupled to the LP shaft **236**, thus, causing the LP shaft **236** to rotate, thereby supporting operation and rotation of the fan section **214** via the LP shaft **236**.

(66) The combustion gases **284** are subsequently routed through the jet exhaust nozzle section **237** of the turbomachine **216** to provide propulsive thrust. Simultaneously, the pressure of the first portion of air **278** is substantially increased as the first portion of air **278** is routed through the bypass airflow passage **248** before being exhausted from a fan nozzle exhaust section **298** of the turbine engine **210**, also providing propulsive thrust.

(67) The turbine engine **210** depicted in FIG. **2** is by way of example only. In other exemplary embodiments, the turbine engine **210** may have any other suitable configuration, as detailed above with respect to FIG. **1**.

(68) FIG. **3** shows a schematic, cross-sectional view of a ducted, indirect-drive, turbine engine **300**, taken along a longitudinal centerline axis **312** of the turbine engine **300**, according to an embodiment of the present disclosure. The turbine engine **300** is similar in some respects to the turbine engine **100** discussed above with respect to FIG. **1**.

(69) As shown in FIG. **3**, the turbine engine **300** includes, in downstream serial flow relationship, a fan section **314** including a fan **302**, a compressor section **316** including a booster or a low-pressure (LP) compressor **321** and a high-pressure (HP) compressor **318**, a combustion section **328** including a combustor **330**, a turbine section **333** including an HP turbine **334** and an LP turbine **320**, and an exhaust nozzle **338**.

(70) The fan section **314** includes a fan casing or a nacelle **340** surrounding the fan **302**. The fan **302** includes a plurality of fan blades **324** disposed radially about the longitudinal centerline axis **312**. The HP compressor **318**, the combustor **330**, and the HP turbine **334** form an engine core **344** of the turbine engine **300**, which generates combustion gases. The engine core **344** is surrounded by a core casing **331**, which is coupled to the nacelle **340**. The nacelle **340** is supported relative to the turbomachine by a plurality of outlet guide vanes **382** that are circumferentially spaced about the core casing **331**.

(71) A high-speed shaft **348** is disposed coaxially about the longitudinal centerline axis **312** of the turbine engine **300** and drivingly connects the HP turbine **334** to the HP compressor **318**. A low-speed shaft **322** (also referred to as a low-pressure shaft), which is disposed coaxially about the

longitudinal centerline axis **312** of the turbine engine **300** and within the larger diameter annular high-speed shaft **348**, drivingly connects the LP turbine **320** to the LP compressor **321**. The low-speed shaft **322** also drivingly connects the LP turbine **320** to the fan **302** through a gearbox assembly **350**. In this way, the turbine engine **300** is considered an indirect drive turbine engine. The high-speed shaft **348** and the low-speed shaft **322** are rotatable about the longitudinal centerline axis **312**.

(72) The LP compressor **321** and the HP compressor **318**, respectively, include a respective plurality of compressor stages **352**, **354**, in which a respective set of compressor blades **356**, **358** rotate relative to a respective set of compressor vanes **360**, **362** to compress or to pressurize gas entering through an inlet **332**. Referring now only to the HP compressor **318**, a single compressor stage **354** includes multiple compressor blades **358** provided on a rotor disk **361** (or blades and a disk are integrated together, referred to as a blisk). A compressor blade extends radially outwardly relative to the longitudinal centerline axis **312**, from a blade platform to a blade tip. Compressor vanes **362** are positioned upstream/downstream of and adjacent to rotating compressor blades **358**. The rotor disk **361** for a stage of compressor blades **358** is mounted to the high-speed shaft **348**. A stage of the HP compressor **318** refers to a single disk of rotor blades or both the rotor blades and adjacent stator vanes (either meaning can apply within the context of this disclosure without loss of clarity).

(73) The HP turbine **334** has one or two stages **364**. In a single turbine stage **364**, turbine blades **368** are provided on a rotor disk **371**. A turbine blade extends radially outwardly relative to the longitudinal centerline axis **312**, from a blade platform to a blade tip. The HP turbine **334** can also include a stator vane **372**. The HP turbine **334** may have both an upstream nozzle adjacent the combustor exit and an exit nozzle aft of the rotor, or a nozzle upstream of rotor blades or downstream of the rotor blades.

(74) Air exiting the HP turbine **334** enters the LP turbine **320** (also referred to as a power turbine), which has a plurality of stages of rotating blades **370**. The LP turbine **320** can have three, four, five, or six stages. In a single LP turbine stage **366** (containing a plurality of blades coupled to the low-speed shaft **322**) a turbine blade is provided on a rotor disk (connected to the low-speed shaft **322**) and extends radially outwardly relative to the longitudinal centerline axis **312**, from a blade platform to a blade tip. The LP turbine **320** can also include a stator vane **374**. The LP turbine **320** may have both an upstream nozzle and an exit nozzle aft of a stage, followed by the exhaust nozzle **338** of the engine.

(75) The turbine engine **300** of FIG. **3** operates in a similar manner as the engine of FIG. **1**. Airflow exiting the fan section **314** is split such that a portion of the airflow is channeled into the inlet **332** to the LP compressor **321**, which then supplies pressurized airflow to the HP compressor **318**, which further pressurizes the air. The pressurized airflow from the HP compressor **318** is mixed with fuel in the combustor **330** and ignited, thereby generating combustion gases. Some work is extracted from the combustion gases by the HP turbine **334**, which drives the HP compressor **318** to produce a self-sustaining combustion. The combustion gases discharged from the HP turbine enter the LP turbine **320**, which extracts additional work to drive the LP compressor **321** and the fan **302** (through the gearbox assembly **350**). The gas discharged from the LP turbine exits through the exhaust nozzle **338**.

(76) Some of the air supplied by the fan **302** bypasses the engine core **344** and is used for cooling of portions, especially hot portions, of the turbine engine **300**, and/or used to cool or to power other aspects of the aircraft. In the context of the turbine engine **300**, the hot portions refer to a variety of portions of the turbine engine **300** downstream of the combustion section **328** (e.g., the turbine section **333**). Other sources of cooling fluid include, but are not limited to, fluid discharged from the LP compressor **321** or the HP compressor **318**.

(77) The turbine engine **300** depicted in FIG. **3** is by way of example only. In other embodiments, the turbine engine may have any other suitable configuration, including, for example, any other

suitable number or configurations of shafts or spools, fan blades, turbines, compressors, or combination thereof. The gearbox assembly may have any suitable configuration, including, for example, a star gear configuration, a planet gear configuration, a single-stage, a multi-stage, epicyclic, non-epicyclic, etc., as detailed further below. The gearbox may have a gear ratio in a range of, for example, 3:1 to 4:1, 3:5 to 4:1, 3.25:1 to 3.5:1, or 4:1 to 5:1. The fan assembly may be any suitable fixed-pitched assembly or variable-pitched assembly. In a variable-pitch assembly, for example, the plurality of fan blades **324** may be controlled to be pitched about a pitch axis P to vary a pitch of the plurality of fan blades **324**. The turbine engine includes additional components not shown in FIG. **3**, such as rotor blades, stator vanes, etc. The fan assembly may be configured in any other suitable manner (e.g., as a fixed pitch fan) and further may be supported using any other suitable fan frame configuration. In some embodiments, the turbine engine **300** can include an interdigitated turbine and gear assembly, and/or can include vaneless counter rotating turbine (VCRT) architecture with an aft gearbox. Aspects of the present disclosure may be incorporated into any other suitable turbine engine, including, but not limited to, turbofan engines, propfan engines, turbojet engines, turboprop, and turboshaft engines.

(78) FIG. **4** shows a schematic view of an unducted, three-stream, turbine engine **410** for an aircraft that may incorporate one or more embodiments of the present disclosure. The turbine engine **410** is a “three-stream engine” in that the architecture of the turbine engine **410** provides three distinct streams (labeled S**1**, S**2**, and S**3**) of thrust-producing airflow during operation, as detailed further below.

(79) As shown in FIG. **4**, the turbine engine **410** defines an axial direction A, a radial direction R, and a circumferential direction C. Moreover, the turbine engine **410** defines a longitudinal centerline axis **412** that extends along the axial direction A. In general, the axial direction A extends parallel to the longitudinal centerline axis **412**, the radial direction R extends outward from, and inward to, the longitudinal centerline axis **412** in a direction orthogonal to the axial direction A, and the circumferential direction C extends three hundred sixty degrees (360°) around the longitudinal centerline axis **412**. The turbine engine **410** extends between a forward end **414** and an aft end **416**, e.g., along the axial direction A.

(80) The turbine engine **410** includes a core engine **420** and a fan assembly **450** positioned upstream thereof. Generally, the core engine **420** includes, in serial flow order, a compressor section, a combustion section, a turbine section, and an exhaust section. Particularly, as shown in FIG. **4**, the core engine **420** includes an engine core **418** and a core cowl **422** that annularly surrounds the core engine **420**. The core engine **420** and the core cowl **422** define a core inlet **424** having an annular shape. The core cowl **422** further encloses and supports a low-pressure (LP) compressor **426** (also referred to as a booster) for pressurizing the air that enters the core engine **420** through core inlet **424**. A high-pressure (HP) compressor **428** receives pressurized air from the LP compressor **426** and further increases the pressure of the air. The pressurized air flows downstream to a combustor **430** where fuel is injected into the pressurized air and ignited to raise the temperature and the energy level of the pressurized air, thereby generating combustion gases.

(81) The combustion gases flow from the combustor **430** downstream to a high-pressure (HP) turbine **432**. The HP turbine **432** drives the HP compressor **428** through a first shaft, also referred to as a high-pressure (HP) shaft **436** (also referred to as a “high-speed shaft **436**”). In this regard, the HP turbine **432** is drivingly coupled with the HP compressor **428**. Together, the HP compressor **428**, the combustor **430**, and the HP turbine **432** define the engine core **418**. The combustion gases then flow to a power turbine or low-pressure (LP) turbine **434**. The LP turbine **434** drives the LP compressor **426** and components of the fan assembly **450** through a second shaft, also referred to as a low-pressure (LP) shaft **438** (also referred to as a “low-speed shaft **438**”). In this regard, the LP turbine **434** is drivingly coupled with the LP compressor **426** and components of the fan assembly **450**. The low-speed shaft **438** is coaxial with the high-speed shaft **436** in the embodiment of FIG. **4**. After driving each of the HP turbine **432** and the LP turbine **434**, the combustion gases exit the core

engine **420** through a core exhaust nozzle **440**. The core engine **420** defines a core flowpath, also referred to as a core duct **442**, that extends between the core inlet **424** and the core exhaust nozzle **440**. The core duct **442** is an annular duct positioned generally inward of the core cowl **422** along the radial direction R.

(82) The fan assembly **450** includes a primary fan **452**. For the embodiment of FIG. **4**, the primary fan **452** is an open rotor fan, also referred to as an unducted fan. However, in other embodiments, the primary fan **452** may be ducted, e.g., by a fan casing or a nacelle circumferentially surrounding the primary fan **452**. The primary fan **452** includes an array of fan blades **454** (only one shown in FIG. **4**). The fan blades **454** are rotatable about the longitudinal centerline axis **412** via a fan shaft **456**. As shown in FIG. **4**, the fan shaft **456** is coupled with the low-speed shaft **438** via a speed reduction gearbox, also referred to as a gearbox assembly **455**, e.g., in an indirect-drive configuration. The gearbox assembly **455** is shown schematically in FIG. **4**. The gearbox assembly **455** includes a plurality of gears for adjusting the rotational speed of the fan shaft **456** and, thus, the primary fan **452** relative to the low-speed shaft **438** to a more efficient rotational fan speed. The gearbox assembly may have a gear ratio of, for example, 4:1 to 12:1, or 7:1 to 12:1, or 4:1 to 10:1, or 5:1 to 9:1, or 6:1 to 9:1, and may be configured in an epicyclic star or a planet gear configuration. The gearbox may be a single stage or a compound gearbox.

(83) The fan blades **454** can be arranged in equal spacing around the longitudinal centerline axis **412**. Each fan blade **454** has a root and a tip, and a span defined therebetween. Each fan blade **454** defines a central blade axis **457**. For the embodiment of FIG. **4**, each fan blade **454** of the primary fan **452** is rotatable about their respective central blade axis **457**, e.g., in unison with one another. One or more actuators **458** are controlled to pitch the fan blades **454** about their respective central blade axis **457**. In other embodiments, each fan blade **454** is fixed or is unable to be pitched about the central blade axis **457**.

(84) The fan assembly **450** further includes a fan guide vane array **460** that includes fan guide vanes **462** (only one shown in FIG. **4**) disposed around the longitudinal centerline axis **412**. For the embodiment of FIG. **4**, the fan guide vanes **462** are not rotatable about the longitudinal centerline axis **412**. Each fan guide vane **462** has a root and a tip, and a span defined therebetween. The fan guide vanes **462** can be unshrouded as shown in FIG. **4** or can be shrouded, e.g., by an annular shroud spaced outward from the tips of the fan guide vanes **462** along the radial direction R. Each fan guide vane **462** defines a central vane axis **464**. For the embodiment of FIG. **4**, each fan guide vane **462** of the fan guide vane array **460** is rotatable about their respective central vane axis **464**, e.g., in unison with one another. One or more actuators **466** are controlled to pitch the fan guide vanes **462** about their respective central vane axis **464**. In other embodiments, each fan guide vane **462** is fixed or is unable to be pitched about the central vane axis **464**. The fan guide vanes **462** are mounted to a fan cowl **470**.

(85) The fan cowl **470** annularly encases at least a portion of the core cowl **422** and is generally positioned outward of the core cowl **422** along the radial direction R. Particularly, a downstream section of the fan cowl **470** extends over a forward portion of the core cowl **422** to define a fan flowpath, also referred to as a fan duct **472**. Incoming air enters through the fan duct **472** through a fan duct inlet **476** and exits through a fan exhaust nozzle **478** to produce propulsive thrust. The fan duct **472** is an annular duct positioned generally outward of the core duct **442** along the radial direction R. The fan cowl **470** and the core cowl **422** are connected together and supported by a plurality of struts **474** (only one shown in FIG. **4**) that extend substantially radially and are circumferentially spaced about the longitudinal centerline axis **412**. The plurality of struts **474** are each aerodynamically contoured to direct air flowing thereby. Other struts in addition to the plurality of struts **474** can be used to connect and to support the fan cowl **470** and/or the core cowl **422**.

(86) The turbine engine **410** also defines or includes an inlet duct **480**. The inlet duct **480** extends between an engine inlet **482** and the core inlet **424** and the fan duct inlet **476**. The engine inlet **482**

is defined generally at the forward end of the fan cowl **470** and is positioned between the primary fan **452** and the fan guide vane array **460** along the axial direction A. The inlet duct **480** is an annular duct that is positioned inward of the fan cowl **470** along the radial direction R. Air flowing downstream along the inlet duct **480** is split, not necessarily evenly, into the core duct **442** and the fan duct **472** by a splitter **484** of the core cowl **422**. The inlet duct **480** is wider than the core duct **442** along the radial direction R. The inlet duct **480** is also wider than the fan duct **472** along the radial direction R.

(87) The fan assembly **450** also includes a mid-fan **486**. The mid-fan **486** includes a plurality of mid-fan blades **488** (only one shown in FIG. **4**). The plurality of mid-fan blades **488** are rotatable, e.g., about the longitudinal centerline axis **412**. The mid-fan **486** is drivingly coupled with the LP turbine **434** via the low-speed shaft **438**. The plurality of mid-fan blades **488** can be arranged in equal circumferential spacing about the longitudinal centerline axis **412**. The plurality of mid-fan blades **488** are annularly surrounded (e.g., ducted) by the fan cowl **470**. In this regard, the mid-fan **486** is positioned inward of the fan cowl **470** along the radial direction R. The mid-fan **486** is positioned within the inlet duct **480** upstream of both the core duct **442** and the fan duct **472**. A ratio of a span of a fan blade **454** to that of a mid-fan blade **488** (a span is measured from a root to tip of the respective blade) is greater than 2 and less than 10, to achieve the desired benefits of the third stream (S**3**), particularly the additional thrust it offers to the engine, which can enable a smaller diameter blade **454** (benefits engine installation).

(88) Accordingly, air flowing through the inlet duct **480** flows across the plurality of mid-fan blades **488** and is accelerated downstream thereof. At least a portion of the air accelerated by the mid-fan blades **488** flows into the fan duct **472** and is ultimately exhausted through the fan exhaust nozzle **478** to produce propulsive thrust. Also, at least a portion of the air accelerated by the plurality of mid-fan blades **488** flows into the core duct **442** and is ultimately exhausted through the core exhaust nozzle **440** to produce propulsive thrust. Generally, the mid-fan **486** is a compression device positioned downstream of the engine inlet **482**. The mid-fan **486** is operable to accelerate air into the fan duct **472**, also referred to as a secondary bypass passage.

(89) During operation of the turbine engine **410**, an initial airflow or an incoming airflow passes through the fan blades **454** of the primary fan **452** and splits into a first airflow and a second airflow. The first airflow bypasses the engine inlet **482** and flows generally along the axial direction A outward of the fan cowl **470** along the radial direction R. The first airflow accelerated by the fan blades **454** passes through the fan guide vanes **462** and continues downstream thereafter to produce a primary propulsion stream or a first thrust stream S**1**. A majority of the net thrust produced by the turbine engine **410** is produced by the first thrust stream S**1**. The second airflow enters the inlet duct **480** through the engine inlet **482**.

(90) The second airflow flowing downstream through the inlet duct **480** flows through the plurality of mid-fan blades **488** of the mid-fan **486** and is consequently compressed. The second airflow flowing downstream of the mid-fan blades **488** is split by the splitter **484** located at the forward end of the core cowl **422**. Particularly, a portion of the second airflow flowing downstream of the mid-fan **486** flows into the core duct **442** through the core inlet **424**. The portion of the second airflow that flows into the core duct **442** is progressively compressed by the LP compressor **426** and the HP compressor **428**, and is ultimately discharged into the combustion section. The discharged pressurized air stream flows downstream to the combustor **330** where fuel is introduced to generate combustion gases or products.

(91) The combustor **430** defines an annular combustion chamber that is generally coaxial with the longitudinal centerline axis **412**. The combustor **430** receives pressurized air from the HP compressor **428** via a pressure compressor discharge outlet. A portion of the pressurized air flows into a mixer. Fuel is injected by a fuel nozzle (omitted for clarity) to mix with the pressurized air thereby forming a fuel-air mixture that is provided to the combustion chamber for combustion. Ignition of the fuel-air mixture is accomplished by one or more igniters (omitted for clarity), and

the resulting combustion gases flow along the axial direction A toward, and into, a first stage turbine nozzle of the HP turbine **432**. A first stage turbine nozzle **433** is defined by an annular flow channel that includes a plurality of radially extending, circumferentially spaced nozzle vanes **435** that turn the combustion gases so that they flow angularly and impinge upon first stage turbine blades of the HP turbine **432**. The combustion gases exit the HP turbine **432** and flow through the LP turbine **434** and exit the core duct **442** through the core exhaust nozzle **440** to produce a core air stream, also referred to as a second thrust stream S**2**. As noted above, the HP turbine **432** drives the HP compressor **428** via the high-speed shaft **436**, and the LP turbine **434** drives the LP compressor **426**, the primary fan **452**, and the mid-fan **486** via the low-speed shaft **438**.

(92) The other portion of the second airflow flowing downstream of the mid-fan **486** is split by the splitter **484** into the fan duct **472**. The air enters the fan duct **472** through the fan duct inlet **476**. The air flows generally along the axial direction A through the fan duct **472** and is ultimately exhausted from the fan duct **472** through the fan exhaust nozzle **478** to produce a third stream, also referred to as a third thrust stream S**3**.

(93) The third thrust stream S**3** is a secondary air stream that increases fluid energy to produce a minority of total propulsion system thrust. In some embodiments, a pressure ratio of the third stream is higher than that of the primary propulsion stream (e.g., a bypass or a propeller driven propulsion stream). The thrust may be produced through a dedicated nozzle or through mixing of the secondary air stream with the primary propulsion stream or a core air stream, e.g., into a common nozzle. In certain embodiments, an operating temperature of the secondary air stream is less than a maximum compressor discharge temperature for the engine. Furthermore, in certain embodiments, aspects of the third stream (e.g., airstream properties, mixing properties, or exhaust properties), and thereby a percent contribution to total thrust, are passively adjusted during engine operation or can be modified purposefully through use of engine control features (such as fuel flow, electric machine power, variable stators, variable inlet guide vanes, valves, variable exhaust geometry, or fluidic features) to adjust or to improve overall system performance across a broad range of potential operating conditions.

(94) The turbine engine **410** depicted in FIG. **4** is by way of example only. In other embodiments, the turbine engine **410** may have any other suitable configuration. For example, in other embodiments, the primary fan **452** may be configured in any other suitable manner (e.g., as a fixed pitch fan) and further may be supported using any other suitable fan frame configuration. In other embodiments, the primary fan **452** can be ducted by a fan casing or a nacelle such that a bypass passage is defined between the fan casing and the fan cowl **470**. Moreover, in other embodiments, any other suitable number or configuration of compressors, turbines, shafts, or a combination thereof may be provided. In still other embodiments, aspects of the present disclosure may be incorporated into any other suitable turbine engine, such as, for example, turbofan engines, propfan engines, turbojet engines, turboprop, turboshaft engines, and/or turbine engines defining two streams (e.g., a bypass stream and a core air stream). In other embodiments, the turbine engine **410** is configured as an unducted, two stream turbine engine such that the turbine engine **410** does not include the fan duct **472**. In some embodiments, the fan guide vane array **460** is configured as a secondary fan such that the fan guide vanes **462** provide a second stage of the primary fan **452** and rotate with respect to the longitudinal centerline axis **412**. In some embodiments, the turbine engine **410** can include an interdigitated turbine and gear assembly, and/or can include vaneless counter rotating turbine (VCRT) architecture with an aft gearbox.

(95) Further, for the depicted embodiment of FIG. **4**, the turbine engine **410** includes an electric machine **490** (motor-generator) operably coupled with a rotating component thereof. In this regard, the turbine engine **410** is a hybrid-electric propulsion machine. Particularly, as shown in FIG. **4**, the electric machine **490** is operatively coupled with the low-speed shaft **438**. The electric machine **490** can be mechanically connected to the low-speed shaft **438**, either directly, or indirectly, e.g., by way of a gearbox assembly **492** (shown schematically in FIG. **4**). Further, although in this

embodiment the electric machine **490** is operatively coupled with the low-speed shaft **438** at an aft end of the low-speed shaft **438**, the electric machine **490** can be coupled with the low-speed shaft **438** at any suitable location or can be coupled to other rotating components of the turbine engine **410**, such as the high-speed shaft **436** or the low-speed shaft **438**. For instance, in some embodiments, the electric machine **490** can be coupled with the low-speed shaft **438** and positioned forward of the mid-fan **486** along the axial direction. In some embodiments the turbine engines of FIGS. **1** to **3** also includes an electric machine coupled to the LP shaft and located in the tail cone of the engine.
(96) In some embodiments, the electric machine **490** can be an electric motor operable to drive or to motor the low-speed shaft **438**, e.g., during an engine burst. In other embodiments, the electric machine **490** can be an electric generator operable to convert mechanical energy into electrical energy. In this way, electrical power generated by the electric machine **490** can be directed to various engine and/or aircraft systems. In some embodiments, the electric machine **490** can be a motor/generator with dual functionality. The electric machine **490** includes a rotor **494** and a stator **496**. The rotor **494** is coupled to the low-speed shaft **438** and rotates with rotation of the low-speed shaft **438**. In this way, the rotor **494** rotates with respect to the stator **496**, thereby generating electrical power. Although the electric machine **490** has been described and illustrated in FIG. **4** as having a particular configuration, the present disclosure may apply to electric machines having alternative configurations. For instance, the rotor **494** and/or the stator **496** may have different configurations or may be arranged in a different manner than illustrated in FIG. **4**.
(97) FIG. **5** is a cross-sectional view of an exemplary turbine engine **500**, taken along a longitudinal centerline axis **512** of the turbine engine **500**, according to the present disclosure. The turbine engine **500** includes a low-pressure (LP) compressor **521**, a high-pressure (HP) compressor **518**, a low-pressure (LP) turbine **520**, and a high-pressure (HP) turbine **534**. These features operate in the same manner as described with respect to FIGS. **1** to **4**. A low-pressure shaft **522** (also referred to as a "low-speed shaft") extends between the low-pressure compressor **521** and the low-pressure turbine **520**. A high-pressure shaft **548** extends between the high-pressure compressor **518** and the high-pressure turbine **534**. Together, the high-pressure compressor **518**, a combustor **530** (e.g., any of the combustors or combustion sections detailed herein), and the high-pressure turbine **534** define an engine core.
(98) The low-pressure shaft **522** is rotationally supported in the turbine engine **500** with one or more bearings. In the embodiment illustrated in FIG. **5**, the turbine engine **500** includes a first bearing **523***a* (also referred to in the art as "Brg 2"), a second bearing **524** (also referred to in the art as "Brg 3"), a third bearing **525** (also referred to in the art as "Brg 4"), and a fourth bearing **523***b* (also referred to in the art as "Brg 5"). The low-pressure shaft **522** is supported by one bearing on a forward side of the core engine (e.g., first bearing **523***a*) and one bearing on an aft side of the core engine (e.g., fourth bearing **523***b*). The high-pressure shaft **548** is supported by the second bearing **524** on a forward side and the third bearing **525** on the aft side. The first bearing **523***a* and the second bearing **524** may be ball bearings, although other types of bearings or rotational supports are contemplated. The third bearing **525** and the fourth bearing **523***b* may be roller bearings, although other types of bearings or rotational supports are contemplated. Although shown as a single bearing at each location, the bearings may be a plurality of bearings. For example, the first bearing **523***a* could comprise two axially spaced bearings.
(99) In FIG. **5**, the length L.sub.MIDSHAFT is a length of a portion of the low-pressure shaft **522**, referred to as a midshaft. The length L.sub.MIDSHAFT is defined between the inboard low-pressure shaft forward bearing (e.g., the first bearing **523***a*) and the inboard low-pressure shaft aft bearing (e.g., the fourth bearing **523***b*). The length L.sub.MIDSHAFT is the lateral distance, parallel to the longitudinal centerline axis **512**, defined between midpoints of the first bearing **523***a* and the fourth bearing **523***b*.
(100) The length L.sub.IGB is the length from the inboard low-pressure shaft forward bearing (e.g.,

the first bearing **523***a*) to the core forward bearing (e.g., the second bearing **524**). The length L.sub.IGB is the lateral distance, parallel to the longitudinal centerline axis **512**, defined between midpoints of the first bearing **523***a* and the second bearing **524**.

(101) The length L.sub.CORE is the length of the engine core (e.g., the length including the high-pressure compressor **518**, the combustor, and the high-pressure turbine **534**). The length L.sub.CORE is defined between the core forward bearing (e.g., the second bearing **524**) and the core aft bearing (e.g., the third bearing **525**). The length L.sub.CORE is the lateral distance, parallel to the longitudinal centerline axis **512**, defined between midpoints of the second bearing **524** and the third bearing **525**. In this way, the length L.sub.CORE is the length of the high-pressure shaft **548** from the second bearing **524** to the third bearing **525**.

(102) The length L.sub.AFT is the length from aft of the core to the inboard low-pressure shaft aft bearing (e.g., the fourth bearing **523***b*). The length L.sub.AFT is the lateral distance, parallel to the longitudinal centerline axis **512**, defined between midpoints of the third bearing **525** and the fourth bearing **523***b*.

(103) The core diameter D.sub.CORE represents the diameter of the engine core. The diameter D.sub.CORE is defined by the outer diameter of the exit from a last stage **517** of the high-pressure compressor **518**, also referred to as the exit stage diameter. In this way, the last stage **517** defines an exit of the HP compressor **518**. The radius of the core is shown in FIG. **5** as D.sub.CORE/2.

(104) FIG. **6** is an enlarged, cross-sectional view of the turbine engine **500**, taken at detail **601** in FIG. **5**, according to the present disclosure. In particular, FIG. **6** shows an enlarged view of the HP compressor **518**, the combustor **530**, and the HP turbine **534**.

(105) The HP compressor **518** includes a plurality of compressor stages **554** (only one of which is labeled in FIG. **6** for clarity), in which a set of HP compressor blades **558** rotate relative to a set of HP compressor vanes **562** to compress or to pressurize gas entering through an HP compressor inlet **515**. The HP compressor inlet **515** is defined by a first compressor stage **554** of the HP compressor **518**. A single HP compressor stage **554** includes multiple compressor blades **558** provided on a rotor disk **561** (or blades and a disk are integrated together, referred to as a blisk). A compressor blade extends radially outwardly relative to the longitudinal centerline axis **512**, from a blade platform to a blade tip. The HP compressor vanes **562** are positioned upstream/downstream of and adjacent to rotating HP compressor blades **558**. The rotor disk **561** for a stage of HP compressor blades **558** is mounted to the high-pressure shaft **548**. A stage of the HP compressor **518** refers to a single disk of rotor blades or both the rotor blades and adjacent stator vanes (either meaning can apply within the context of this disclosure without loss of clarity).

(106) The HP turbine **534** has one or two HP turbine stages **564**. In a single HP turbine stage **564**, HP turbine blades **568** are provided on a rotor disk **571**. A turbine blade extends radially outwardly relative to the longitudinal centerline axis **512**, from a blade platform to a blade tip. The HP turbine **534** can also include an HP turbine stator vane **572**. The HP turbine **534** may have both an upstream nozzle adjacent the combustor exit and an exit nozzle aft of the rotor, or a nozzle upstream of rotor blades or downstream of the rotor blades.

(107) In FIG. **6**, the radius R.sub.HUB,IN is a radius of a hub **563** at the HP compressor inlet **515**. The radius R.sub.HUB,IN is defined from the longitudinal centerline axis **512** to the hub **563** at the HP compressor inlet **515** in the radial direction. The radius R.sub.TIP,IN is a radius of a tip **565** of the HP compressor blade **558** of the first stage (e.g., at the HP compressor inlet **515**). The radius R.sub.TIP,IN is defined from the longitudinal centerline axis **512** to the tip **565** of the HP compressor blade **558** at the HP compressor inlet **515** in the radial direction.

(108) The radius R.sub.HUB,EX is a radius of the hub **563** at the last stage **517** (e.g., at the exit of the HP compressor **518**). The radius R.sub.HUB,EX is defined from the longitudinal centerline axis **512** to the hub **563** at the last stage **517** in the radial direction. The radius R.sub.TIP,EX is a radius of the tip **565** of the HP compressor blade **558** of the last stage **517** of the HP compressor **518**. The radius R.sub.TIP,EX is defined from the longitudinal centerline axis **512** to the tip **565** of the HP

compressor blade **558** at the last stage **517** of the HP compressor **518** in the radial direction. In this way, the radius R.sub.TIP,EX corresponds to the radius of the core D.sub.CORE/2.

(109) FIGS. **7**A to **7**C show a schematic view of a high-pressure shaft (HP shaft) corresponding to the predominate three typical mode shapes of the HP shaft that need to be taken into consideration when designing an engine core and avoiding dynamic instability in the HP shaft, as realized by the inventors. For example, the HP shaft illustrated in FIGS. **7**A to **7**C can be the high-pressure shaft **548** of FIGS. **5** and **6**. The HP shaft extends from the HP compressor to the HP turbine. The deformed HP shaft is supported by the HP shaft forward and aft bearings **702** and **704**, respectively. The bearings are represented by their stiffnesses (shown as springs). FIG. **7**A illustrates a first mode, also referred to as a fundamental bounce mode, also known as a bow rotor mode, of the high-pressure shaft **700**. The first mode can occur at sub-idle speeds of the high-pressure shaft, which are about sixty percent to eighty percent below a redline speed of the high-pressure shaft (e.g., about forty percent below cruise speeds). In FIG. **7**B, the high-pressure shaft **700** has a second mode, also known as the pitch mode. The second mode occurs at near to cruise speeds of the high-pressure shaft, which are about twenty percent to thirty percent below the high-pressure shaft redline speeds. In FIG. **7**C, the high-pressure shaft **700** has a third mode, also known as a S-shaped mode. The third mode occurs near redline speeds of the high-pressure shaft.

(110) As mentioned earlier, the inventors sought to improve upon the operating speed of a high-speed shaft, also referred to as the high-pressure shaft. With regard to the speed of the high-pressure shaft, consideration was given not simply to those factors (e.g., the length of the engine core, the diameter of the engine core, or the number of stages present in the HP compressor or the HP turbine) affecting the high-speed shaft, but also to factors considering the inlet temperature of the HP compressor and the inlet corrected flow. In contrast to existing gas turbine engines requiring higher bypass ratios and smaller engine cores, embodiments considered presented challenges in determining how the engine core (e.g., the HP shaft) could be reduced in size without operating at or near the Alford margin and/or the third mode margin of the HP shaft, while enabling higher bypass ratio engines and without affecting performance of the HP compressor and/or the HP turbine.

(111) A selection of HP compressor sizes and HP shaft sizes takes into consideration other factors, some of which can limit the selection of a shaft. The inventors, however, realized during the course of making the several embodiments referred to in the foregoing that there is a particular range of designs, and constraints on feasible designs that provided an unexpected benefit. The interplay among components can make it particularly difficult to select or to develop one component during engine design and prototype testing, especially when some components are at different stages of completion. For example, one or more components may be nearly complete, yet one or more other components may be in an initial or a preliminary phase where only one (or a few) design parameters are known. It is desired to arrive at what is possible at an early stage of design, so that the down selection of candidate optimal designs, given the tradeoffs, become more possible. Heretofore, the process has sometimes been more ad hoc, selecting one design or another without knowing the impact when a concept is first taken into consideration.

(112) Even taken separately from the integration of a shaft design with the rest of an engine, modifying an existing shaft to increase the redline speed of the shaft is challenging, and the impact of the different types of improvements and configurations on redline speed is not easily predictable without empirical experimentation and simulation, which can be enormously expensive and time-consuming. In some cases, a modification may even result in lowering the redline speed. For example, to reduce HP compressor length, the number of HP compressor stages can be reduced and the pressure ratio can be reduced. Further, transferring the pressure ratio to the LP compressor results in higher HP compressor inlet temperature and reduced HP compressor inlet corrected flow, both of which result in higher redline speed and, hence, reduced Alford margin and/or reduced third mode margin.

(113) As part of this effort, the inventors evaluated the influence of using different materials for the engine core (rotor disks, airfoils) and changes in radius (e.g., changes in the radius ratio of the core), and their impact on the HP compressor pressure ratio and the inlet temperature and the resulting impact that these modifications have on the dynamics of the high-speed shaft, the low-speed shaft, and the interaction between these two shafts as can occur through dynamic excitation transmitted through shaft bearings. Next generation engines will operate with a higher power density (power/weight), which can mean lengthening the core by adding additional compression stages to the high-pressure compressor. Additionally, or alternatively, a core operating at a higher power density is expected to operate at higher temperatures at the compressor exit stage and the downstream turbine stages. In this regard, higher-temperature-tolerant material can be used to enable operating at higher temperatures, such as, a ceramic matrix composite (CMC) material. The use of such higher temperature-tolerant material is expected to bring about changes in weight and component size and volume, which is expected to influence the behavior of both the high-speed shaft and the low-speed shaft. Thus, the inventors, as part of their investigation and evaluation of different engine architectures, also considered how the dynamics of the low-speed shaft and the high-speed shaft might change when the engine core changes in size and weight, in response to a need to operate at higher power densities enabled by use of higher temperature-tolerant material.
(114) CMC material is expected to be used in the HPT, LPT, and HPC parts of a core engine as this type of material can withstand higher temperatures than more traditional metal alloys. Given the differences in material properties for a CMC material, particularly, the higher strength to weight ratio (or higher specific modulus) of CMC versus a metal alloy used in existing gas turbine engines in use currently, there is a need to ascertain the expected effects on HP shaft dynamics and LP shaft dynamics. Use of a CMC material introduces opportunities to increase a critical speed of the LP shaft, not only due to a weight reduction but also in making more space available for increasing the LP shaft diameter extending through the core given the higher strength of these materials. The components made, at least in-part, from CMC material may include the HP compressor rotors and disks, the HP turbine nozzles and/or rotors and rotor disks, and the LP turbine nozzles and/or rotors and disks. CMC allows for components to be made more stiff or reduced in size while having the same strength properties as metal alloys, thereby having equivalent capability for sustaining high stresses associated with centrifugal forces at high temperatures and operating speeds, in addition to reducing the weight of the core, as compared to metals. CMC also introduces new and untested structural dynamics, which can introduce tradeoffs or compromise among a desired aero-performance (temperatures, rotation rates, pressure ratios) and stable dynamics at cruise, takeoff/max thrust and redline speeds for both the HP shaft and LP shaft. Accordingly, components of the HP compressor and/or components of the HP turbine in the embodiments 1 to 120 in TABLES 1 to 5 below can be made from CMC. For example, rotors, blades, blades and discs, a single stage, or multiple stages in the high-pressure compressor module and/or in the high-pressure turbine module may be formed partially or wholly of CMC.
(115) The inventors also found, during the course of evaluating several different core designs (designs that reduce the size of the engine core) from the perspective of maintaining dynamic stability among the HP shaft the following relationships. These relationships take into account the trade-offs that need to be made, so that the design accounts not only for features of the core length, size and weight, and representative of a higher overall pressure ratio and increased operating temperatures, but also the effects that these changes in the core can have on the HP compressor inlet temperature and the inlet corrected flow that affect the HP shaft redline speed.
(116) A first relationship concerns the high-pressure shaft redline speed, or high-speed shaft rating HSR given by (1):
(117) $$HSR = \frac{1}{k} * N2_{r/l} * D_{CORE} * \left(\frac{L_{CORE}}{D_{CORE}}\right)^2 \quad (1)$$
(118) L.sub.CORE and D.sub.CORE are defined as described previously, and

L.sub.CORE/D.sub.CORE is a ratio of the length of the engine core to the diameter of the engine core. N2.sub.r/l is the redline speed for the HP shaft, for example, reported in the engine Type Certificate Data Sheet (TCDS), and k is a constant with a value of 10.sup.6 inch-RPM. The redline speed N2.sub.r/l is from 10,580 RPM to 35,788 RPM. L.sub.CORE is from 36.4 inches (in) to 66.8 inches (in). D.sub.CORE is from 9.4 inches to 31.8 inches. HSR is from 1.5 to 6.2.

(119) For stable operating conditions, the high-pressure shaft third mode should be placed as a percentage below the redline speed of the HP shaft or above the redline speed of the HP shaft and satisfying (2a), (2b), (2c), or (2d):

$$-0.1>(-0.1822*HSR+HST)>0 \quad (2a)$$

$$-0.2>(-0.1822*HSR+HST)>0 \quad (2b)$$

$$-0.3>(-0.1822*HSR+HST)>0 \quad (2c)$$

$$(-0.1822*HSR+HST)>-0.1 \quad (2d)$$

(120) HST accounts for the effects that the HPC pressure ratio and the HPC exit temperature can have on the third mode. T25 is the temperature in Rankine (° R) at the high-pressure compressor (HPC) inlet. A good approximation for HST can be made in terms of only the T25, using (3):

$$HST=-0.726*T25/T.\text{sub.STD}+1.61 \quad (3)$$

where T25 is from 579° R to 803° R, HST is from 0.49 to 0.8, and T.sub.STD is the standard temperature defined by a constant value of 518.67° R.

(121) For stable operating conditions, the high-pressure shaft second mode is a function of the minimum speed of the HP shaft at cruise as a percentage of the redline speed of the HP shaft. For example, for stable operating conditions, the high-pressure shaft second mode should satisfy (4):

(122) $(-0.1215*HSR+(\frac{2*HST-1}{3}))<-0.1 \quad (4)$

(123) Relationships (2a) to (2d) and (4) account for individual configurations of the HP shaft that have variations in mode margin due to additional parameters, such as, for example, the bearing support stiffness, additional mass added for maintainability, and/or features such as power screws. For example, if the excess margin is 20% of the third mode, but the second mode is at −10% margin, then the mitigation is to soften the bearing support such that the third mode margin falls to 10% and the second mode margin becomes −20%. Accordingly, the relationships (2a) to (2d) and (4) provide for providing a balance among the third mode margin and the second mode margin of the HP shaft.

(124) Such a configuration of the high-pressure shaft third mode in relationships (2a) to (2d) accounts for stable operating conditions while considering variations in architectural differences in various types of turbine engines, as well as ensuring that the HP shaft is not excessively excited at the high-pressure shaft second mode during high power steady state operations (e.g., cruise, climb, and/or takeoff). For example, the third mode margin can be −10% of the redline speed of the HP shaft per relationship (2a), −20% of the redline speed of the HP shaft per relationship (2b), or −30% of the redline speed of the HP shaft per relationship (2c). The third mode margin can also be greater than −10% of the redline speed of the HP shaft per relationship (2d) to account for the architectural differences in various types of turbine engines. For example, the third mode may fall within −10% of redline speed of the HP shaft and the bearing support structure can be stiffened or softened to move the third mode margin to just above the redline speed of the HP shaft.

(125) Further, such a configuration of the high-pressure shaft second mode in relationship (4) accounts for stable operating conditions while considering variations in architectural differences in various types of turbine engine, as well as ensuring that the HP shaft is not excessively excited at the high-pressure shaft second mode during high power steady state operations (e.g., cruise, climb, and/or takeoff). For example, the second mode margin can be −10% of the redline speed of the HP shaft per relationship (4).

(126) Another relationship for HSR concerns the low-pressure shaft redline speed, or high-speed shaft rating HSR.sub.LP given by (5):

(127) $\mathrm{HSR}_{LP} = \frac{1}{k} * N1_{r/1} * D_{CORE} * \left(\frac{L_{CORE}}{D_{CORE}}\right)^2$ (5)

(128) L.sub.CORE and D.sub.CORE are defined as described previously. N1r/1 is the redline speed for the LP shaft, for example, reported in the engine Type Certificate Data Sheet (TCDS), and k is a constant with a value of 10.sup.6 inch-RPM. For stable operating conditions, the high-pressure shaft first mode is a function of the minimum speed of the LP shaft at cruise as a percentage of the redline speed of the LP shaft. For example, for stable operating conditions, the high-pressure shaft first mode is placed either below (as a percentage) or just above the redline speed of the LP shaft satisfying relationship (6a), (6b), (6c), or (6d):

(129) $-0.1 > \left(\frac{0.55}{(\mathrm{HSR}_{LP})^2} + LST\right) > 0$ (6*a*) $-0.2 > \left(\frac{0.55}{(\mathrm{HSR}_{LP})^2} + LST\right) > 0$ (6*b*)

$-0.3 > \left(\frac{0.55}{(\mathrm{HSR}_{LP})^2} + LST\right) > 0$ (6*c*) $\left(\frac{0.55}{(\mathrm{HSR}_{LP})^2} + LST\right) > -0.1$ (6*d*)

(130) LP Speed Temperature Correction (LST) accounts for the effects that the HPC pressure ratio and the HPC exit temperature can have on the first mode. T25 is the temperature in Rankine (° R) at the high-pressure compressor (HPC) inlet. A good approximation for LST can be made in terms of only the T25, using (7):

LST=−1.193**T*25/*T*.sub.STD+1.18 (7)

where T25 is from 579° R to 803° R, LST is from −0.15 to −0.67, and T.sub.STD is the standard temperature defined by a constant value of 518.67° R.

(131) Relationships (1) through (7) when used individually or together (depending on application or changes made to a design) can identify an improved core accounting for characteristics associated with a higher power density (use of CMC material, increased number of HPC and/or HPT stages, increased bore height or length of the LP shaft) and bounding those features within constraints to avoid dynamic instability by interaction between one or more vibration modes of the LP shaft and HP shaft. Further, relationships (6a) to (6d) account for individual configurations of the HP shaft that have variations in mode margin due to additional parameters, such as, for example, the bearing support stiffness, additional mass added for maintainability, and/or features such as power screws. For example, if the first mode is within −20% of the redline speed of the LP shaft (e.g., is between the redline speed of the LP shaft and −20% of the redline speed of the LP), then the mitigation is to either soften or to stiffen the bearing support such that the first mode margin falls below −20% of the redline speed of the LP shaft or above the redline speed of the LP shaft. Such a configuration of the high-pressure shaft first mode in relationships (6a) to (6d) accounts for stable operating conditions while considering variations in architectural differences in various types of turbine engine, as well as ensuring that the HP shaft is not excessively excited at the high-pressure shaft first mode during high power steady state operations (e.g., cruise, climb, and/or takeoff). For example, the first mode margin can be −10% of the redline speed of the LP shaft per relationship (6a), −20% of the redline speed of the LP shaft per relationship (6b), or −30% of the redline speed of the LP shaft per relationship (6c). The first mode margin can also be greater than −10% of the redline speed of the LP shaft per relationship (6d) to account for the architectural differences in various types of turbine engines. For example, the first mode may fall within −10% of redline speed of the LP shaft and the bearing support structure can be stiffened or softened to move the first mode margin to just above the redline speed of the LP shaft.

(132) The area of the exit of the HP compressor (e.g., area at the last stage of the HP compressor), also referred to as the HP compressor exit flow area, provides a measure of the bypass ratio (BPR) of the engine. As mentioned earlier, as the BPR increases (e.g., BPR greater than 8.0, greater than 10.0, or greater than 12.0), the engine core size (e.g., the HP compressor exit flow area) decreases and the L.sub.CORE/D.sub.CORE increases, thereby making it challenging to meet the HP shaft third mode margins. To ensure stable operation of the HP shaft, the L.sub.CORE/D.sub.CORE is from 2.1 to 4.3. As detailed further below with respect to FIGS. **8** and **9**, a first relationship concerns the L.sub.CORE/D.sub.CORE as a function of a first high-speed shaft operating

parameter HSP.sub.X that is given by the following relationship (8):

(133) $$\mathrm{HSP}_X = \frac{(A_{ex})^2 * P_{STD} * OPR_{T/O}}{FN_{T/O} * (N_{Stg}/10)^2} \quad (8)$$

where P.sub.STD is standard pressure (e.g., absolute pressure of one atmosphere) defined by a constant value of 14.696 psi (or 14.7 psi), FN.sub.T/O is sea-level static thrust at takeoff flight conditions corresponding to a maximum thrust rating for an engine core configuration, for example, reported in the engine Type Certificate Data Sheet (TCDS) and is from 12,675 lbf to 107,480 lbf, OPR.sub.T/O is the overall pressure ratio of the engine at takeoff flight conditions corresponding to the maximum thrust rating for an engine core configuration reported in, for example, ICAO ENGINE nvPM EMISSIONS DATA SHEET and is from 26.3 to 82, N.sub.Stg is the number of stages in the HP compressor and is 8, 9, 10, or 11, and A.sub.EX is the area of the HP compressor exit and is provided by the following relationship (9):
A.sub.EX=π*(*R*.sub.TIP,EX.sup.2−*R*.sub.HUB,EX.sup.2) (9)
where R.sub.TIP,EX and R.sub.HUB,EX are measured as detailed above with respect to FIG. **6**. A.sub.EX is from 11 in.sup.2 to 95 in.sup.2.
(134) As alluded to earlier, the inventors further considered the effects of the HP compressor inlet temperature and the inlet corrected flow on the HP shaft redline speed. Based on the studies done, it was found unexpectedly that there are certain relationships among the HP compressor inlet temperature and the inlet corrected flow at takeoff flight conditions, and the HP dynamics that influence the design of the engine core from the perspective of maintaining stable dynamics during engine operations.
(135) A second relationship concerns the HP compressor tip radius ratio and the HP compressor area ratio, referred to as an area ratio high-speed shaft rating (HSP.sub.AR) and is given by (10):

(136) $$\mathrm{HSP}_{AR} = \frac{\left(\frac{L_{core}}{D_{core}}\right)^2 * AR}{\sqrt{\frac{R_{\mathrm{HUB,IN}}}{R_{\mathrm{TIP,IN}}}} * \sqrt{\frac{R_{\mathrm{TIP,EX}}}{R_{\mathrm{TIP,IN}}}}} \quad (10)$$

where R.sub.HUB,IN/R.sub.TIP,IN is referred to as the inlet radius ratio, R.sub.TIP,EX/R.sub.TIP,IN is referred to as the HP compressor tip radius ratio, and AR is the area ratio of the compressor and is the ratio of the area at the inlet of the HP compressor to the area at the exit of the HP compressor (A.sub.IN/A.sub.EX). A.sub.IN is the HP compressor inlet flow area and is given by the following relationship (11):
A.sub.IN=π*(*R*.sub.TIP,IN.sup.2−*R*.sub.HUB,IN.sup.2) (11)
where R.sub.TIP,IN and R.sub.HUB,IN are measured as detailed above with respect to FIG. **6**. AR is from 5.6 to 13.9, the inlet radius ratio is from 0.4 to 0.6, R.sub.TIP,EX is from 4.73 in. to 15.83 in., and R.sub.TIP,IN is from 5.68 in. to 16.32 in.
(137) A third relationship concerns the HP compressor tip radius ratio and the HP compressor inlet area, referred to as an inlet area high-speed shaft rating (HSP_A.sub.IN) and is given by (12):

(138) $$\mathrm{HSP\_A}_{\mathrm{IN}} = \frac{\left(\frac{L_{core}}{D_{core}}\right)^2 * A_{IN}}{\sqrt{\frac{R_{\mathrm{HUB,IN}}}{R_{\mathrm{TIP,IN}}}} * \sqrt{\frac{R_{\mathrm{TIP,EX}}}{R_{\mathrm{TIP,IN}}}}} \quad (12)$$

where R.sub.HUB,IN/R.sub.TIP,IN is referred to as the inlet radius ratio, R.sub.TIP,EX/R.sub.TIP,IN is referred to as the HP compressor tip radius ratio, and A N is the area at the inlet of the HP compressor. A.sub.IN is from 85 in.sup.2 to 703 in.sup.2.
(139) As detailed further below with respect to FIG. **12**, HSP_A.sub.IN is a function of a second high-speed shaft operating parameter (HSP.sub.X1). HSP.sub.X1 is given by (13):

(140) $$\mathrm{HSP}_{X1} = \frac{A_{EX} * 1000}{FN_{T/O} * (N_{Stg}/10)^2} \quad (13)$$

(141) OPR.sub.T/O is the overall pressure ratio of the engine at takeoff flight conditions and is from 26.3 to 82, FN.sub.T/O is sea-level static thrust at takeoff flight conditions and is from 12,674 lbf to 107,480 lbf, and A.sub.EX is the area of the HP compressor exit and is provided by relationship (9) above.

(142) A fourth relationship concerns the HP compressor exit rim speed, the HP compressor exit temperature, and the HP compressor stage count, referred to as an exit rim speed high-speed shaft rating (HSP_U.sub.RIM,R/L) and is given by (14):

(143) $$\text{HSP\_U}_{\text{RIM},R/L} = \frac{\left(\frac{L_{CORE}}{D_{CORE}}\right)^2}{N_{stg} * A_{F,\text{IN}}^{1/3}} * \left(\frac{T3_{T/O}}{U_{\text{RIM},R/L}}\right)^3 \quad (14)$$

where N.sub.stg is the number of stages of the HP compressor and is 8, 9, 10, or 11, T3.sub.T/O is the exit temperature of the HP compressor at takeoff flight conditions and is from 1455° R to 2020° R, A.sub.F,IN is the frontal area of the HP compressor, and U.sub.RIM,R/L is the exit rim speed of the HP compressor at redline speeds (e.g., the rotational speed of the exit stage of the HP compressor at the hub of the exit stage). A.sub.F,IN is given by (15):
A.sub.F,IN=π*(*R*.sub.TIP,IN) (15)
(144) The frontal area A.sub.F,IN is from 101 in.sup.2 to 837 in.sup.2, and R.sub.TIP,IN is from 5.68 in to 16.32 in. U.sub.RIM,R/L is given by (16):

(145) 0 $$U_{\text{RIM},R/L} = \frac{*N2_{R/L}}{30} * \frac{R_{\text{HUB},EX}}{12} \quad (16)$$ where N2.sub.R/L is in RPM, R.sub.HUB,EX is in inches and U.sub.RIM,R/L is in ft/s.
(146) The exit rim speed of the HP compressor U.sub.RIM,R/L is from 1,347 ft/s to 1,557 ft/s, the redline speed of the HP compressor N2.sub.R/L is from 10,580 RPM to 35,788 RPM, and R.sub.HUB,EX is from 4.31 in to 14.85 in. T3.sub.T/O is from 1,455° R to 2,020° R, and is given by (17):

(147) $$T3_{T/O} = T25_{T/O} * (3.465 * \text{AR} - 5.7)^{\frac{-1}{*\ \text{Poly}}} \quad (17)$$

where T25.sub.T/O is the HP compressor inlet temperature at takeoff flight conditions, AR is the area ratio of the HP compressor, γ is the gas constant of air and is equal to 1.37, η.sub.Poly is the compressor efficiency and is approximately equal to 0.9. T25.sub.T/O is from 579° R to 803° R and is given by (18):

(148) $$T25_{T/O} = T_{ISA} * \left(\frac{1.25 * OPR_{T/O}}{3.465 * AR - 5.7}\right)^{\frac{-1}{.\text{Math.}\ \text{Poly}}} + T_{IC} \quad (18)$$

where T.sub.ISA is ambient temperature and is approximately equal to 545.67° R, OPR.sub.T/O is the overall pressure ratio of the engine at takeoff flight conditions, γ is the gas constant of air and is equal to 1.37, η.sub.Poly is the compression efficiency and is approximately equal to 0.9, T.sub.IC is the intercooler temperature drop (e.g., reduction) at takeoff flight conditions upstream of the HP compressor (e.g., between the LP compressor and the HP compressor), and is from −100° R to 0° R, AR is the area ratio of the compressor and is the ratio of the area at the inlet of the HP compressor to the area at the exit of the HP compressor (A.sub.IN/A.sub.EX).
(149) A fifth relationship concerns the HP compressor tip radius ratio and HP compressor inlet temperature, referred to as a radius ratio high-speed shaft rating (HSP.sub.RR) and is given by (19):

(150) $$\text{HSP}_{RR} = \frac{\left(\frac{L_{core}}{D_{core}} * \frac{T25_{T/O}}{T_{STD}}\right)^2}{\sqrt{\frac{R_{\text{HUB, IN}}}{R_{\text{TIP, IN}}}} * \sqrt{\frac{R_{\text{TIP, EX}}}{R_{\text{TIP, IN}}}}} \quad (19)$$

where R.sub.HUB,IN/R.sub.TIP,IN is referred to as the inlet radius ratio, R.sub.TIP,EX/R.sub.TIP,IN is referred to as the HP compressor tip radius ratio, T.sub.STD is the standard temperature and is equal to 518.67° R, and T25.sub.T/O is the HP compressor inlet temperature at takeoff flight conditions. The T25.sub.T/O is given by the relationship (18) above.
(151) As discussed above, the HP compressor inlet temperature and the inlet corrected flow impact the HP shaft redline speed. The lower HP compressor inlet temperature and the higher inlet corrected flow at the takeoff flight conditions can be obtained by: 1. Increased HP compressor pressure ratio with low HP compressor inlet radius ratio, higher HP compressor exit radius, or higher HP compressor stage count, 2. Intercooling the HP compressor inlet air, 3. Lowering the HP compressor inlet pressure, 4. Water/steam ingestion forward of the HP compressor inlet, 5. Lower specific (corrected) flow, 6. Lower exhaust gas temperature (EGT), 7. Lower OPR or BPR. The

lower HP compressor inlet radius ratio and the water/steam ingestion have favorable effects on performance (e.g., increase performance of the HP compressor), the higher HP compressor exit radius, the higher HP compressor stage count, the intercooling, the lowering HP compressor inlet pressure, and the lower specific flow have minor effects on the performance of the HP compressor, while the lower exhaust gas temperature and the lower OPR or BPR have negative effects on the overall engine performance.

(152) Accordingly, the relationships (1) to (19) detailed herein when used together or individually can identify an improved engine core accounting for characteristics associated with lower HP compressor inlet temperatures and higher HP compressor inlet corrected flow, accounting for the factors and tradeoffs discussed above, and bounding those features within constraints to avoid dynamic instability by interaction between one or more vibration modes of the HP shaft. For example, the relationships (1) to (19) results in the unexpected result of lowering the HP compressor tip radius ratio and increasing the HP compressor pressure ratio, thereby lowering the HP compressor inlet temperature at a fixed OPR and increasing the HP compressor inlet corrected flow while accounting for a feasible L.sub.CORE/D.sub.CORE for avoiding undesired HP shaft dynamics (e.g., the Alford stability and/or the third mode of the HP shaft). Thus, the inventors have unexpectedly discovered the relationships detailed above among the L.sub.CORE/D.sub.CORE, the HP compressor inlet radius ratio, the HP compressor exit radius, and/or the HP compressor inlet temperature and the HP compressor inlet corrected flow, for optimizing performance (e.g., higher T3 or OPR, and/or larger HP compressor blade heights and/or improved clearance) at optimal L.sub.CORE/D.sub.CORE. The relationships detailed above also account for a feasible dynamics margin design space for HP compressor stage count of 9, 10, or greater, and/or for 8 stages at lower HP compressor tip radius ratios with improved performance. The relationships, thus, provide for higher OPR or BPR or exhaust gas temperature configurations with HP compressor stage counts of 8 or greater and either subcritical or supercritical midshaft of the LP shaft.

(153) TABLES 1 to 6 list embodiments of the HP compressor and the HP shaft along with their associated HSR, HSR.sub.LP, L.sub.CORE/D.sub.CORE, HSP.sub.AR, HSP_A.sub.IN, HSP_U.sub.RIM,R/L, and HSP.sub.RR values. TABLES 1 to 6 include embodiments 1 to 120 and show values for various parameters of each of the relationships (1) to (19) detailed above. The parameters shown in each of TABLES 1 to 6 can be combined such that each embodiment 1 to 120 includes values for every parameter shown in TABLES 1 to 6.

(154) TABLE 1 lists embodiments of HSR and HSR.sub.LP, along with the associated N2.sub.R/L and N1.sub.R/L values. The embodiments inform of the dimensions or qualities of the HP compressor, the HP shaft, and the LP shaft that are believed reasonable and practical for the HP compressor, the HP shaft, and the LP shaft for providing a balance among improving the third mode margin of the HP shaft, without overly reducing performance of the HP compressor and/or the HP turbine. In other words, the HSR and HSR.sub.LP indicates the operating ranges of interest, taking into account the constraints in which the HP compressor operates, e.g., the HP compressor inlet temperature and the HP compressor inlet corrected flow, that have not been previously considered in HP compressor and HP shaft designs, as detailed above, as well as ensuring the HP dynamics do not excite the LP shaft and vice-versa.

(155) TABLE-US-00001 TABLE 1 N2.sub.R/L L.sub.CORE/ N1.sub.R/L Emb. (RPM) D.sub.CORE HSR HST (RPM) HSR.sub.LP LST 1 24788 3.4 3.9 0.56 10137 1.6 −0.54 2 23020 2.9 2.9 0.57 9772 1.2 −0.53 3 22481 2.9 3.1 0.64 8515 1.2 −0.41 4 22417 3.0 3.2 0.64 8515 1.2 −0.41 5 22246 2.8 2.6 0.57 9772 1.2 −0.53 6 20928 2.9 2.8 0.59 10137 1.3 −0.49 7 19967 2.8 2.6 0.63 10137 1.3 −0.44 8 21281 2.6 2.5 0.56 9772 1.1 −0.54 9 21695 2.8 2.7 0.56 9772 1.2 −0.54 10 19922 3.0 2.9 0.56 9346 1.4 −0.54 11 20809 2.7 2.7 0.52 9346 1.2 −0.61 12 20809 2.5 2.3 0.52 9346 1.0 −0.61 13 20809 2.3 1.9 0.57 9346 0.8 −0.52 14 35788 4.3 6.2 0.59 8771 1.5 −0.50 15 35788 4.0 5.5 0.64 8771 1.4 −0.42 16 12306 2.1 1.5 0.70 10393 1.2 −0.32 17 10580 2.1 1.5 0.64 7748 1.1 −0.42 18 24181 2.8 2.7 0.58 10632 1.2 −0.51 19 23523

2.7 2.7 0.53 10076 1.2 −0.59 20 18378 2.2 1.7 0.73 9791 0.9 −0.27 21 18401 2.3 1.7 0.67 9696 0.9 −0.37 22 21259 2.5 2.2 0.65 10096 1.0 −0.39 23 23255 2.8 2.7 0.67 10423 1.2 −0.37 24 20398 2.5 2.1 0.66 10329 1.1 −0.38 25 24432 2.8 2.9 0.55 10616 1.3 −0.57 26 19914 2.4 2.0 0.77 10539 1.1 −0.20 27 19790 2.4 2.0 0.73 10174 1.0 −0.26 28 24618 3.0 3.1 0.67 11814 1.5 −0.36 29 23073 2.7 2.6 0.67 10795 1.2 −0.36 30 24152 2.9 2.9 0.66 11535 1.4 −0.38 31 24437 2.8 2.8 0.64 11113 1.3 −0.41 32 23043 2.7 2.6 0.61 10323 1.2 −0.47 33 20310 2.5 2.1 0.77 10081 1.1 −0.20 34 23662 2.7 2.6 0.70 11102 1.2 −0.31 35 24039 2.8 2.8 0.69 11420 1.3 −0.32 36 20133 2.6 2.3 0.69 9988 1.1 −0.34 37 20410 2.7 2.6 0.61 9229 1.2 −0.45 38 22900 2.9 3.0 0.58 9844 1.3 −0.51 39 28164 3.6 4.3 0.68 9745 1.5 −0.35 40 25626 3.6 4.5 0.58 6545 1.2 −0.51 41 23225 3.3 3.6 0.64 7866 1.2 −0.41 42 21410 3.3 3.5 0.69 8122 1.3 −0.34 43 19521 2.8 2.6 0.58 9891 1.3 −0.51 44 18233 2.8 2.6 0.62 9936 1.4 −0.45 45 19710 2.6 2.2 0.54 11250 1.3 −0.58 46 18510 2.6 2.2 0.61 11406 1.3 −0.47 47 15207 2.5 2.1 0.72 11633 1.6 −0.28 48 17374 2.4 1.9 0.62 12784 1.4 −0.44 49 20022 2.7 2.7 0.61 9295 1.3 −0.46 50 19304 2.4 2.0 0.57 11428 1.2 −0.53 51 17220 2.4 2.0 0.65 11778 1.3 −0.40 52 18140 2.2 1.7 0.59 12842 1.2 −0.50 53 16123 2.2 1.7 0.66 13224 1.4 −0.38 54 18670 2.5 2.1 0.64 11034 1.3 −0.41 55 15873 2.3 1.9 0.73 11849 1.4 −0.26 56 27161 2.8 2.9 0.65 8771 0.9 −0.40 57 22208 2.4 2.1 0.78 10971 1.0 −0.18 58 24006 2.6 2.6 0.61 9004 1.0 −0.47 59 20495 2.3 1.9 0.64 11554 1.1 −0.41 60 17397 2.1 1.7 0.73 12849 1.2 −0.26 61 24405 2.3 2.1 0.49 9321 0.8 −0.67 62 18478 2.2 1.8 0.74 12364 1.2 −0.25 63 19700 2.3 2.0 0.61 10906 1.1 −0.47 64 20730 2.5 2.2 0.77 8367 0.9 −0.20 65 26513 3.0 3.5 0.58 8624 1.1 −0.52 66 20516 2.8 2.7 0.69 8012 1.1 −0.33 67 27440 3.1 3.4 0.61 9166 1.1 −0.46 68 22948 2.8 2.7 0.58 9942 1.2 −0.51 69 23902 2.7 2.8 0.64 9569 1.1 −0.41 70 23444 2.9 2.9 0.53 6816 0.9 −0.59 71 22409 2.4 2.1 0.67 8736 0.8 −0.36 72 26430 2.8 2.9 0.59 7546 0.8 −0.50 73 24926 3.2 3.5 0.65 9124 1.3 −0.40 74 24030 2.9 3.0 0.72 7481 0.9 −0.28 75 24497 3.1 3.4 0.73 8976 1.2 −0.27 76 25286 3.0 3.3 0.61 9854 1.3 −0.46 77 27176 2.9 3.2 0.49 6886 0.8 −0.66 78 24306 3.1 3.1 0.72 10523 1.4 −0.28 79 21613 2.4 2.0 0.66 9631 0.9 −0.38 80 27294 3.4 4.0 0.70 8494 1.2 −0.31 81 26052 3.6 4.2 0.71 8157 1.3 −0.31 82 26029 3.5 4.2 0.67 8882 1.4 −0.37 83 21762 2.7 2.6 0.72 7908 0.9 −0.29 84 24839 3.4 3.8 0.60 8481 1.3 −0.48 85 25546 3.1 3.4 0.54 9088 1.2 −0.57 86 23396 3.0 3.2 0.78 10436 1.4 −0.19 87 21419 2.7 2.5 0.76 8521 1.0 −0.21 88 26095 3.1 3.4 0.70 9709 1.3 −0.32 89 23364 2.9 2.9 0.72 9835 1.2 −0.28 90 24653 3.4 3.9 0.74 8923 1.4 −0.25 91 23589 3.3 3.7 0.59 8376 1.3 −0.50 92 20805 2.7 2.5 0.80 8693 1.0 −0.15 93 23344 3.2 3.6 0.60 6345 1.0 −0.48 94 26303 3.4 4.0 0.72 8481 1.3 −0.29 95 23050 2.7 2.5 0.71 8264 0.9 −0.30 96 23094 3.3 3.6 0.65 8411 1.3 −0.39 97 24334 3.4 3.8 0.72 7411 1.2 −0.29 98 24109 2.8 2.8 0.73 9936 1.2 −0.26 99 27525 3.1 3.5 0.65 8938 1.1 −0.39 100 26067 2.8 3.1 0.49 7071 0.8 −0.66 101 24924 3.1 3.4 0.52 9768 1.3 −0.60 102 25797 3.6 4.3 0.70 8334 1.4 −0.31 103 24704 3.4 4.0 0.65 8037 1.3 −0.40 104 26645 3.4 3.8 0.61 9325 1.3 −0.46 105 23578 3.3 3.7 0.71 8428 1.3 −0.30 106 27652 3.4 3.9 0.66 8802 1.2 −0.38 107 21015 3.1 3.3 0.66 8078 1.3 −0.39 108 24454 2.7 2.6 0.66 9936 1.1 −0.38 109 25294 2.8 2.9 0.68 9283 1.1 −0.35 110 24002 3.3 3.8 0.68 8082 1.3 −0.35 111 25956 3.2 3.6 0.62 9610 1.3 −0.45 112 23911 3.2 3.5 0.69 8746 1.3 −0.33 113 24993 3.1 3.3 0.55 6672 0.9 −0.56 114 24106 2.8 2.8 0.64 7524 0.9 −0.42 115 26699 3.1 3.6 0.59 7611 1.0 −0.49 116 24229 2.9 3.2 0.65 8541 1.1 −0.39 117 21483 2.6 2.4 0.68 7855 0.9 −0.34 118 23965 3.0 3.2 0.64 8443 1.1 −0.42 119 26550 2.9 3.1 0.53 7813 0.9 −0.59 120 24214 3.1 3.2 0.61 8266 1.1 −0.46

(156) With reference to TABLE 1, N2.sub.R/L is in a range from 10,580 RPM to 35,788 RPM, HSR is in a range from 1.5 to 6.2, HST is in a range from 0.49 to 0.8, N1.sub.R/L is in a range from 6,345 RPM to 13,225 RPM, HSR.sub.LP is in a range from 0.8 to 1.6, and LST is in a range from −0.15 to −0.67.

(157) TABLE 2 lists embodiments of the HP compressor and the HP shaft along with the associated HSR and L.sub.CORE/D.sub.CORE values of the HP compressor and the HP shaft. The embodiments inform of the dimensions or qualities of the HP compressor and the HP shaft that are believed reasonable and practical for the HP compressor and the HP shaft for providing a balance

among improving the third mode margin of the HP shaft, without overly reducing performance of the HP compressor and/or the HP turbine. In other words, the HSR and the L.sub.CORE/D.sub.CORE ratio indicates the operating ranges of interest, taking into account the constraints in which the HP compressor operates, e.g., the HP compressor inlet temperature and the HP compressor inlet corrected flow, that have not been previously considered in HP compressor and HP shaft designs, as detailed above.

(158) TABLE-US-00002 TABLE 2 FN.sub.T/O EGT.sub.T/O N2.sub.R/L R.sub.TIP,EX R.sub.HUB,EX A.sub.EX L.sub.CORE L.sub.CORE/ Emb. (lbf) (° C.) (RPM) OPR.sub.T/O N.sub.Stg (in) (in) (in.sup.2) (in) D.sub.CORE HSR HSP.sub.X 1 35940 1113 24788 49.5 10 6.9 6.39 21 46.5 3.4 3.9 9.3 2 36228 1113 23020 44.1 9 7.6 7.1 22 43.9 2.9 2.9 10.8 3 36228 1175 22481 41.8 10 7.9 7.39 22 46.2 2.9 3.1 8.5 4 36228 1175 22417 40.7 10 7.7 7.26 22 46.8 3.0 3.2 7.7 5 36228 1113 22246 44.1 9 7.8 7.31 23 43 2.8 2.6 12.2 6 36228 1113 20928 44.1 10 8 7.43 29 46.2 2.9 2.8 15.1 7 36228 1113 19967 44.1 11 8.4 7.78 32 47.2 2.8 2.6 15 8 3628 1113 21281 44.1 9 8.4 7.86 26 43.9 2.6 2.5 15.5 9 36228 1113 21695 44.1 9 8 7.5 25 44.9 2.8 2.7 13.5 10 39515 1113 19922 44.1 9 8.4 7.8 32 49.8 3.0 2.9 20.6 11 39515 1113 20809 44.1 8 8.8 8.11 34 47.7 2.7 2.7 30.4 12 27633 1113 20809 37.4 8 8.8 8.11 34 43.7 2.5 2.3 36.9 13 19324 1113 20809 31.7 8 8.8 8.11 34 39.7 2.3 1.9 44.7 14 18124 1113 35788 40.9 9 4.7 4.31 12 40.3 4.3 6.2 5.7 15 12674 1113 35788 34.6 9 4.7 4.31 12 38.2 4.0 5.5 6.9 16 75161 1113 12306 47.8 10 13 12.57 68 56.2 2.1 1.5 43 17 107480 1113 10580 56.4 10 16 14.85 95 66.8 2.1 1.5 69.1 18 25247 1063 24181 44.9 8 7.4 6.83 24 40.9 2.8 2.7 24.2 19 25288 1080 23523 41.7 8 7.6 7.06 26 41.7 2.7 2.7 25.4 20 29198 1158 18378 32.5 8 9.2 8.7 30 40.9 2.2 1.7 23.4 21 26169 1208 18401 26.3 8 9.2 8.6 34 41.7 2.3 1.7 26 22 23249 1088 21259 32.5 8 8.2 7.59 28 40.9 2.5 2.2 25.7 23 29699 1071 23255 53.5 9 7.4 6.94 22 41.7 2.8 2.7 16.2 24 20081 1073 20398 32.5 9 8.2 7.72 26 40.9 2.5 2.1 19.5 25 27940 1102 24432 62.9 9 7.4 6.93 19 41.7 2.8 2.9 14.8 26 24574 1074 19914 53.5 10 8.6 8.3 18 41.7 2.4 2 10.1 27 28698 1119 19790 53.4 10 8.5 8.12 19 40.9 2.4 2 10.2 28 22111 1160 24618 53.5 10 7 6.67 15 41.7 3.0 3.1 8.4 29 24668 1079 23073 62.9 10 7.5 7.17 16 40.9 2.7 2.6 9.7 30 25477 1186 24152 62.9 10 7.2 6.83 15 41.7 2.9 2.9 7.6 31 26508 1103 24437 82 10 7.2 6.93 13 40.9 2.8 2.8 8.1 32 31781 1128 23043 62.9 10 7.7 7.3 20 41.7 2.7 2.6 11.7 33 29444 1134 20310 34.9 8 8.6 8.06 29 42.4 2.5 2.1 22.3 34 25868 1165 23662 40.6 8 7.4 6.86 22 40.3 2.7 2.6 17.3 35 25169 1135 24039 51.2 9 7.4 7.03 18 41.9 2.8 2.8 12.5 36 29459 1107 20133 43 9 8.7 8.16 26 44.5 2.6 2.3 17.7 37 30518 1065 20410 58.8 10 8.7 8.28 22 47 2.7 2.6 13.9 38 25749 1069 22900 64.6 10 7.8 7.4 18 45.4 2.9 3 11.6 39 18136 1113 28164 40.6 10 5.8 5.48 11 41.9 3.6 4.3 4.3 40 36229 1113 25626 40.7 9 6.6 6.03 24 48.3 3.6 4.5 11.4 41 36254 1113 23225 40.6 10 7.2 6.66 23 47.3 3.3 3.6 8.8 42 36253 1113 21410 40.4 10 7.7 7.23 23 50.3 3.3 3.5 8.6 43 52524 1113 19521 40.7 9 8.6 7.92 34 48.2 2.8 2.6 16.5 44 52523 1113 18233 41 9 9.1 8.48 34 51.2 2.8 2.6 16.6 45 52525 1113 19710 40.1 9 8.5 7.85 36 43.7 2.6 2.2 17.7 46 52561 1113 18510 40.7 10 9 8.36 35 46 2.6 2.2 13.9 47 52558 1113 15207 40.1 10 11 10.17 34 54.1 2.5 2.1 12.7 48 52560 1113 17374 40.6 10 9.5 8.9 34 45.2 2.4 1.9 13.1 49 52523 1113 20022 40.8 9 8.9 8.3 34 49 2.7 2.7 16.8 50 52524 1113 19304 40.8 9 9.3 8.61 36 44.2 2.4 2 18.2 51 52522 1113 17220 40.9 9 10 9.65 34 48.1 2.4 2 16.7 52 52523 1113 18140 40.8 9 9.8 9.16 35 43.2 2.2 1.7 17.1 53 52522 1113 16123 40.8 9 11 10.31 33 47.2 2.2 1.7 15.8 54 52560 1113 18670 40.7 10 9.5 8.9 35 46.7 2.5 2.1 14 55 52558 1113 15873 39.9 10 11 10.47 34 51.5 2.3 1.9 13.3 56 18124 1113 27161 40.8 9 6.7 6.42 12 37.6 2.8 2.9 5.7 57 18136 1113 22208 39.4 10 8.3 8.04 12 39.4 2.4 2.1 4.7 58 36228 1113 54006 40.9 9 7.9 7.4 24 41.6 2.6 2.6 11.8 59 36228 1113 20495 41 9 9.1 8.67 24 41.3 2.3 1.9 12.1 60 36228 1113 17397 40.2 9 11 10.21 24 45 2.1 1.7 11.4 61 36230 1113 24405 40.1 9 7.8 7.28 27 36.4 2.3 2.1 14.4 62 36253 1113 18478 39.8 10 10 9.61 24 43.6 2.2 1.8 9.5 63 52523 1113 19700 40.9 9 9.6 9.02 36 44.7 2.3 2 17.9 64 29791 1141 20730 46.7 10 8.7 8.42 16 42.9 2.5 2.2 5.6 65 38564 1123 26513 48.5 8 7.1 6.58 21 43.1 3.0 3.5 13 66 41861 1258 20516 39.3 10 8.3 7.81 22 46.9 2.8 2.7 6.7 67 34695 1249 27440 40.3 9 6.7 6.2 19 40.8 3.1 3.4 7.4 68 45080 1187 22948 40.2 9 7.6 6.99 26 42.5 2.8 2.7 11.1 69 38835 1252 23902 42.3 8 7.8 7.37 19 42.6 2.7

2.8 9.4 70 41411 1128 23444 39.3 8 7.6 7 29 43.7 2.9 2.9 17.7 71 40010 1281 22409 44.2 9 8.3 7.93 18 39.9 2.4 2.1 6.8 72 34589 1261 26430 40.1 8 7.1 6.62 19 39 2.8 2.9 9.5 73 36392 1184 24926 45.2 10 6.7 6.3 18 43.6 3.2 3.5 6.1 74 29097 1266 24030 46.7 9 7.4 7.07 13 42.5 2.9 3 5.1 75 29975 1273 24497 47.3 10 7.1 6.77 13 44.3 3.1 3.4 4 76 35983 1230 25286 38.4 8 7.1 6.62 21 43.2 3.0 3.3 10.3 77 35202 1136 27176 39.2 8 6.9 6.33 26 40.4 2.9 3.2 16.8 78 28834 1252 24306 42.3 10 6.9 6.54 14 42.2 3.1 3.1 4.2 79 38443 1282 21613 38.2 9 8.5 8.13 20 40.2 2.4 2 7.5 80 27754 1263 27294 43.6 10 6.2 5.82 13 42.4 3.4 4 4.1 81 27382 1156 26052 43.3 10 6.4 5.96 15 45.4 3.6 4.2 5.4 82 34118 1225 26029 48.9 10 6.4 5.99 15 45.2 3.5 4.2 4.8 83 41362 1282 21762 48.9 10 8 7.65 17 43.3 2.7 2.6 4.9 84 33372 1118 24839 44.3 10 6.8 6.35 20 46 3.4 3.8 7.9 85 44425 1118 25546 43.2 9 7 6.29 28 43.2 3.1 3.4 13.4 86 28190 1269 23396 45.3 10 7.5 7.19 13 45.3 3.0 3.2 3.8 87 35231 1273 21419 47.9 10 8.1 7.83 15 43.4 2.7 2.5 4.3 88 28272 1262 26095 44.8 10 6.7 6.33 13 41.4 3.1 3.4 4.1 89 42416 1282 23364 48.5 10 7.6 7.26 17 43.9 2.9 2.9 4.9 90 28346 1263 24653 40 10 6.8 6.49 15 46.4 3.4 3.9 4.5 91 43315 1115 23589 41.3 9 7.2 6.59 27 47.4 3.3 3.7 12.5 92 33540 1259 20805 47.8 10 8.5 8.24 14 45.2 2.7 2.5 4.3 93 42603 1139 23344 41.4 9 7.4 6.8 26 47.5 3.2 3.6 12.1 94 29583 1278 26303 47.6 10 6.5 6.13 13 44.3 3.4 4 3.8 95 31357 1281 23050 41.7 10 7.6 7.24 15 40.7 2.7 2.5 4.7 96 44345 1215 23094 42.4 10 7.3 6.78 23 47.5 3.3 3.6 7.2 97 36178 1233 24334 45.9 10 6.9 6.5 17 46.5 3.4 3.8 5.2 98 33158 1260 24109 46 10 7.4 7.02 15 41.6 2.8 2.8 4.4 99 32153 1279 27525 48.7 10 6.6 6.27 14 40.9 3.1 3.5 4.3 100 44003 1118 26067 48.4 8 7.4 6.78 26 41.9 2.8 3.1 17.6 101 42640 1127 24924 41.3 9 6.9 6.22 27 43 3.1 3.4 13.1 102 30510 1281 25797 39.3 10 6.4 6.02 16 46 3.6 4.3 4.7 103 39341 1137 24704 43.8 9 6.9 6.37 22 47.6 3.4 4 9.7 104 38354 1216 26645 43.6 10 6.3 5.83 19 42.8 3.4 3.8 6.3 105 39061 1277 23578 48.7 10 7 6.64 16 46.9 3.3 3.7 4.6 106 34146 1256 27652 45.3 10 6.2 5.83 16 41.9 3.4 3.9 4.9 107 44129 1158 21015 42.1 10 7.9 7.38 25 49.6 3.1 3.3 8.5 108 39281 1281 24454 47.1 9 7.5 7.13 17 40.3 2.7 2.6 6.1 109 27391 1213 25294 45 9 7.2 6.87 14 40.6 2.8 2.9 5.8 110 36428 1203 24002 43.8 10 7 6.61 19 47.1 3.3 3.8 6.2 111 45242 1281 25956 44.8 10 6.7 6.15 20 42.8 3.2 3.6 6.1 112 31468 1271 23911 46.1 10 6.9 6.55 14 44.7 3.2 3.5 4.2 113 44365 1118 24993 44.5 9 7 6.32 27 42.7 3.1 3.3 13.1 114 40875 1186 24106 46.7 8 7.7 7.31 20 42.6 2.8 2.8 11 115 38425 1246 26699 40.3 9 6.8 6.28 21 42.5 3.1 3.6 8.6 116 42939 1208 24229 44.4 8 7.6 7.14 21 44.7 2.9 3.2 10.8 117 38881 1139 21483 46.8 9 8.5 8.13 20 43.8 2.6 2.4 9.1 118 43139 1250 23965 43.5 10 7.3 6.8 21 44.3 3.0 3.2 6.5 119 36707 1195 26550 40.8 8 7.2 6.66 23 41.1 2.9 3.1 13 120 43047 1201 24214 42.7 10 7.2 6.65 23 43.8 3.1 3.2 7.7

(159) The ranges of FN.sub.T/O, N2.sub.R/L, OPR.sub.T/O, R.sub.HUB,EX, A.sub.EX, L.sub.CORE, and L.sub.CORE/D.sub.CORE are detailed above. HSR is given by relationship (1) above and is from 1.5 to 6.2. The exhaust gas temperature (EGT) is from 1,063° C. to 1,282° C. at redline speeds of the HP shaft. The EGT is a measure of BPR of the turbine engine along with the fan diameter. The EGT is limited by material capability of the LP turbine inlet blades. For example, the LP turbine inlet blades can include metallic single crystal blades uncooled (e.g., minimum capability), cooled (+200° C.), or CMC blade uncooled (+100° C. to +150° C.). The fan diameter is a function of the thrust requirement, and the core size is decided by the EGT and the OPR. In general, lower FN.sub.T/O, higher EGT, and/or higher OPR.sub.T/O results in lower core size (e.g., lower L.sub.CORE and lower D.sub.CORE), but higher L.sub.CORE/D.sub.CORE, higher N2R/L, and higher HSR, and, thus, making it more challenging to meet dynamics margins (e.g., Alford stability and/or third mode margin). Accordingly, embodiments 1 to 120 provide for lowering the core size, while accounting for the dynamics margins and overall engine performance.

(160) FIG. **8** represents, in graph form, the L.sub.CORE/D.sub.CORE as a function of the HSP.sub.X. HSP.sub.X is given by relationship (8) detailed above. L.sub.CORE/D.sub.CORE is in a range from 2.1 to 4.3 and HSP.sub.X is in a range from 3.8 in.sup.2 to 69.1 in.sup.2. An area **800** represents the boundaries of L.sub.CORE/D.sub.CORE and HSP.sub.X. L.sub.CORE/D.sub.CORE and HSP.sub.X are bounded by an upper bound **802**. The upper bound **802** is given by (20):

$$L\text{.sub.CORE}/D\text{.sub.CORE}<\text{MAX}(4.8-0.088*(HSP\text{.sub.X}),3.18-0.015*(HSP\text{.sub.X})) \qquad (20)$$

(161) With reference to TABLE 2 and FIG. **8**, in general, L.sub.CORE/D.sub.CORE decreases as HSP.sub.X increases, and L.sub.CORE/D.sub.CORE increases as HSP.sub.X decreases. HSP.sub.X increases with increased A.sub.EX and/or increases OPR.sub.T/O, and decreases with increased FN.sub.T/O. The area **800** shows the behavior of lower core size, leading to higher L.sub.CORE/D.sub.CORE due to L.sub.CORE not scaling with flow size, as detailed above. For direct drive engines, reducing the core size leads to an increase in L.sub.CORE/D.sub.CORE (e.g., up to 3.25), which has an effect on the dynamics margins, thereby limiting the design of the engine core. For geared engines (e.g., indirect drive), the L.sub.CORE/D.sub.CORE is limited to about 3.0, which has been achieved with 8 stage compressors. The BPR can be increased in three ways: 1. Increased thrust from the same engine core size by increasing the fan size, 2. Smaller engine core size with increased OPR by increasing the LP compressor pressure ratio or increasing T25, or 3. Smaller engine core size with increased EGT. All three methods of increasing the BPR lead to lowering the HSP.sub.x, thereby increasing L.sub.CORE/D.sub.CORE. To increase L.sub.CORE/D.sub.CORE with minimal effects on the dynamics margins, the HP compressor tip radius ratio is increased, and the number of HP compressor stages is reduced. Additionally, smaller blade heights at the HP compressor exit can be utilized.
(162) Accordingly, the area **800** illustrates feasible dynamics zone for higher stage count compressors with higher L.sub.CORE/D.sub.CORE than engines without the benefit of the present disclosure (e.g., engines at lower HSP.sub.x). This is achieved by balancing the HP compressor inlet temperature, corrected inlet flows, and higher HP compressor pressure ratios with the radius ratio.
(163) FIG. **9** represents, in graph form, the L.sub.CORE/D.sub.CORE as a function of the HSP.sub.X, according to another embodiment. HSP.sub.X is given by relationship (8) detailed above. L.sub.CORE/D.sub.CORE is in a range from 2.1 to 4.35 and HSP.sub.X is in a range from 3.86 in.sup.2 to 69.2 in.sup.2. An area **900** represents the boundaries of L.sub.CORE/D.sub.CORE and HSP.sub.X. L.sub.CORE/D.sub.CORE and HSP.sub.X are bounded by an upper bound **902**. The upper bound **902** is given by (21):
(164) $\frac{L_{CORE}}{D_{CORE}} < \frac{4.08}{(\mathrm{HSP}_X - 8)^{0.14}}$ (21)
(165) With reference to TABLE 2 and FIG. **9**, in general, L.sub.CORE/D.sub.CORE decreases as HSP.sub.X increases, and L.sub.CORE/D.sub.CORE increases as HSP.sub.X decreases, as detailed above. HSP.sub.X increases with increased A.sub.EX and/or increases OPR.sub.T/O, and decreases with increased FN.sub.T/O, as detailed above.
(166) TABLE 3 lists embodiments of the HP compressor and the HP shaft along with the associated HSP.sub.AR values of the HP compressor and the HP shaft. The embodiments inform of the dimensions or qualities of the HP compressor and the HP shaft that are believed reasonable and practical for the HP compressor and the HP shaft for providing a balance among improving the third mode margin of the HP shaft, without overly reducing performance of the HP compressor and/or the HP turbine. In other words, the HSP.sub.AR indicates the operating range of interest, taking into account the constraints in which the HP compressor operates, e.g., the HP compressor inlet temperature and the HP compressor inlet corrected flow, that have not been previously considered in HP compressor and HP shaft designs, as detailed above.
(167) TABLE-US-00003 TABLE 3 FN.sub.T/O R.sub.HUB,IN/ R.sub.TIP,IN R.sub.TIP,EX A.sub.IN A.sub.EX HSP.sub.X Emb. (lbf) OPR.sub.T/O N.sub.Stg R.sub.TIP,IN (in) (in) (in.sup.2) (in.sup.2) AR (in.sup.2) HSP.sub.AR 1 35940 49.5 10 0.47 8.35 6.9 170 21 7.9 9.3 144 2 36228 44.1 9 0.56 8.68 7.58 162 22 7.3 10.8 87 3 36228 41.8 10 0.47 8.85 7.86 192 22 8.6 8.5 115 4 36228 40.7 10 0.47 8.6 7.72 181 22 8.4 7.7 118 5 36228 44.1 9 0.56 8.9 7.8 171 23 7.3 12.2 79 6 36228 44.1 10 0.56 10.25 8.03 227 29 7.8 15.1 97 7 36228 44.1 11 0.56 11.2 8.41 270 32 8.5 15 103 8 36228 44.1 9 0.56 9.4 8.38 190 26 7.2 15.5 70 9 36228 44.1 9 0.56 9.1 8.01 178 25 7.2 13.5 80 10 39515 44.1 9 0.56 10.35 8.43 230 32 7.2 20.6 93 11 39515 44.1 8

0.57 10.25 8.76 223 34 6.5 30.4 69 12 27633 37.4 8 0.57 9.69 8.76 199 34 5.8 36.9 50 13 19324 31.7 8 0.57 9.69 8.76 199 34 5.8 44.7 41 14 18124 40.9 9 0.4 5.68 4.73 85 12 7.2 5.7 228 15 12674 34.6 9 0.4 5.68 4.73 85 12 7.2 6.9 205 16 75161 47.8 10 0.4 13.98 13.4 516 68 7.6 43 54 17 107480 56.4 10 0.4 16.32 15.83 703 95 7.4 69.1 53 18 25247 44.9 8 0.52 8.02 7.37 148 24 6.1 24.2 68 19 25288 41.7 8 0.56 8.76 7.62 165 26 6.4 25.4 68 20 29198 32.5 8 0.57 10.07 9.24 213 30 7.1 23.4 48 21 26169 26.3 8 0.58 9.96 9.2 207 34 6.2 26 44 22 23249 32.5 8 0.54 9.2 8.17 190 28 6.7 25.7 61 23 29699 53.5 9 0.47 8.37 7.43 172 22 7.7 16.2 95 24 20081 32.5 9 0.54 9.09 8.23 184 26 7.1 19.5 63 25 27940 62.9 9 0.56 8.23 7.35 145 19 7.6 14.8 86 26 24574 53.5 10 0.5 9.06 8.64 194 18 10.9 10.1 92 27 28698 53.4 10 0.55 9.55 8.49 201 19 10.4 10.2 87 28 22111 53.5 10 0.46 7.39 7.03 136 15 8.8 8.4 118 29 24668 62.9 10 0.53 8.45 7.52 162 16 10.1 9.7 109 30 25477 62.9 10 0.54 7.91 7.16 139 15 9.6 7.6 116 31 26508 82 10 0.57 8.16 7.23 141 13 10.5 8.1 118 32 31781 62.9 10 0.43 8.21 7.73 173 20 8.6 11.7 99 33 29444 34.9 8 0.46 9.13 8.61 207 29 7.2 22.3 67 34 25868 40.6 8 0.52 8.11 7.35 151 22 6.9 17.3 76 35 25169 51.2 9 0.44 7.6 7.43 147 18 8 12.5 97 36 29459 43 9 0.47 9.12 8.65 202 26 7.8 17.7 77 37 30518 58.8 10 0.51 9.72 8.69 219 22 9.9 13.9 107 38 25749 64.6 10 0.55 9.01 7.77 177 18 10 11.6 123 39 18136 40.6 10 0.54 6.89 5.8 106 11 9.2 4.3 178 40 36229 40.7 9 0.4 7.95 6.62 167 24 7.1 11.4 163 41 36254 40.6 10 0.4 8.53 7.19 192 23 8.3 8.8 155 42 36253 40.4 10 0.4 9.03 7.71 215 23 9.4 8.6 171 43 52524 40.7 9 0.54 10.46 8.59 243 34 7.1 16.5 84 44 52523 41 9 0.54 10.97 9.1 268 34 7.8 16.6 93 45 52525 40.1 9 0.6 10.6 8.54 226 36 6.3 17.7 59 46 52561 40.7 10 0.54 10.91 9 265 35 7.6 13.9 74 47 52558 40.1 10 0.54 12.48 10.69 347 34 10.3 12.7 97 48 52560 40.6 10 0.6 11.55 9.49 268 34 7.9 13.1 63 49 52523 40.8 9 0.4 9.99 8.94 263 34 7.6 16.8 96 50 52524 40.8 9 0.54 10.57 9.25 249 36 6.9 18.2 57 51 52522 40.9 9 0.54 11.4 10.2 289 34 8.4 16.7 68 52 52523 40.8 9 0.6 11.17 9.75 251 35 7.2 17.1 49 53 52522 40.8 9 0.6 12.09 10.81 294 33 8.8 15.8 57 54 52560 40.7 10 0.4 10.55 9.51 294 35 8.4 14 84 55 52558 39.9 10 0.4 11.82 10.98 369 34 10.7 13.3 97 56 18124 40.8 9 0.6 7.06 6.71 100 12 8.5 5.7 88 57 18136 39.4 10 0.54 8.26 8.27 152 12 12.5 4.7 96 58 36228 40.9 9 0.4 8.32 7.9 182 24 7.6 11.8 86 59 36228 41 9 0.54 9.56 9.1 203 24 8.4 12.1 60 60 36228 40.2 9 0.54 10.72 10.57 256 24 10.8 11.4 67 61 36230 40.1 9 0.6 8.66 7.84 151 27 5.6 14.4 41 62 36253 39.8 10 0.4 10.08 10.01 268 24 11 9.5 83 63 52523 40.9 9 0.4 10.12 9.62 270 36 7.6 17.9 66 64 29791 46.7 10 0.46 8.88 8.71 194 16 12.4 5.6 111 65 38564 48.5 8 0.45 7.87 7.08 156 21 7.3 13 108 66 41861 39.3 10 0.45 9.07 8.25 205 22 9.3 6.7 117 67 34695 40.3 9 0.45 7.51 6.66 142 19 7.6 7.4 113 68 45080 40.2 9 0.54 9.14 7.57 185 26 7.1 11.1 83 69 38835 42.3 8 0.53 8.55 7.78 165 19 8.5 9.4 92 70 41411 39.3 8 0.51 8.69 7.62 174 29 6.1 17.7 75 71 40010 44.2 9 0.54 8.53 8.29 161 18 8.7 6.8 70 72 34589 40.1 8 0.55 7.86 7.06 135 19 7.1 9.5 77 73 36392 45.2 10 0.48 8.02 6.74 155 18 8.4 6.1 138 74 29097 46.7 9 0.56 8.03 7.36 140 13 10.6 5.1 124 75 29975 47.3 10 0.45 7.56 7.08 143 13 10.9 4 165 76 35983 38.4 8 0.51 8.03 7.1 151 21 7.4 10.3 102 77 35202 39.2 8 0.45 7.58 6.94 143 26 5.6 16.8 73 78 28834 42.3 10 0.55 7.91 6.88 138 14 9.8 4.2 134 79 38443 38.2 9 0.55 8.83 8.52 171 20 8.4 7.5 64 80 27754 43.6 10 0.47 7.19 6.17 126 13 9.5 4.1 175 81 27382 43.3 10 0.42 7.46 6.35 144 15 9.5 5.4 203 82 34118 48.9 10 0.49 7.71 6.38 142 15 9.4 4.8 185 83 41362 48.9 10 0.53 8.96 7.99 182 17 10.9 4.9 117 84 33372 44.3 10 0.43 7.91 6.83 160 20 8 7.9 148 85 44425 43.2 9 0.43 8.17 6.96 172 28 6.2 13.4 100 86 28190 45.3 10 0.41 7.78 7.46 158 13 12.4 3.8 182 87 35231 47.9 10 0.53 8.98 8.12 182 15 12.4 4.3 127 88 28272 44.8 10 0.49 7.3 6.66 127 13 9.6 4.1 138 89 42416 48.5 10 0.41 8.43 7.63 186 17 10.9 4.9 149 90 28346 40 10 0.4 7.88 6.84 164 15 11.1 4.5 216 91 43315 41.3 9 0.45 8.86 7.21 196 27 7.3 12.5 129 92 33540 47.8 10 0.45 8.93 8.52 200 14 13.9 4.3 150 93 42603 41.4 9 0.44 8.82 7.39 198 26 7.6 12.1 129 94 29583 47.6 10 0.46 7.4 6.45 135 13 10.7 3.8 198 95 31357 41.7 10 0.56 8.55 7.57 158 15 10.2 4.7 105 96 44345 42.4 10 0.4 8.73 7.29 201 23 8.9 7.2 163 97 36178 45.9 10 0.41 8.11 6.89 172 17 10.3 5.2 199 98 33158 46 10 0.48 8.11 7.35 158 15 10.8 4.4 131 99 32153 48.7 10 0.41 6.94 6.61 125 14 9 4.3 138 100 44003 48.4 8 0.44 7.93 7.37 159 26 6 17.6 76 101 42640 41.3 9 0.51 8.56 6.89 171 27 6.3 13.1 96 102 30510 39.3 10 0.41 7.61 6.42 152 16 9.6 4.7 211 103 39341 43.8 9 0.41 8.26 6.9 178 22 8.1 9.7 165 104 38354

43.6 10 0.45 7.59 6.33 144 19 7.4 6.3 137 105 39061 48.7 10 0.49 8.39 7.01 168 16 10.6 4.6 185 106 34146 45.3 10 0.44 7.32 6.24 136 16 8.6 4.9 159 107 44129 42.1 10 0.44 9.29 7.9 219 25 8.9 8.5 144 108 39281 47.1 9 0.55 8.24 7.5 149 17 8.9 6.1 91 109 27391 45 9 0.53 7.5 7.19 126 14 9.1 5.8 101 110 36428 43.8 10 0.41 8.35 7.04 182 19 9.7 6.2 184 111 45242 44.8 10 0.43 7.81 6.65 156 20 7.6 6.1 130 112 31468 46.1 10 0.55 7.83 6.89 135 14 9.6 4.2 147 113 44365 44.5 9 0.49 8.52 6.97 174 27 6.5 13.1 96 114 40875 46.7 8 0.5 8.51 7.74 171 20 8.4 11 94 115 38425 40.3 9 0.4 7.62 6.8 153 21 7.2 8.6 118 116 42939 44.4 8 0.44 8.37 7.6 178 21 8.3 10.8 114 117 38881 46.8 9 0.48 8.96 8.52 194 20 9.5 9.1 93 118 43139 43.5 10 0.43 8.39 7.28 181 21 8.7 6.5 132 119 36707 40.8 8 0.45 7.54 7.18 143 23 6.3 13 79 120 43047 42.7 10 0.42 8.39 7.18 182 23 7.9 7.7 123

(168) The embodiments 1 to 120 of TABLE 3 are the same as the embodiments 1 to 120 of TABLES 1 and 2, but TABLE 3 includes parameters in the HSP.sub.AR relationship (10) above. The ranges of FN.sub.T/O, N2.sub.R/L, OPR.sub.T/O, N.sub.STG, R.sub.HUB,IN/R.sub.TIP,IN, R.sub.TIP,IN, R.sub.TIP,EX, A.sub.IN, A.sub.EX, AR, and L.sub.CORE/D.sub.CORE are detailed above. In general, lower FN.sub.T/O, higher EGT, and/or higher OPR.sub.T/O results in lower core size (e.g., lower L.sub.CORE and lower D.sub.CORE), but higher L.sub.CORE/D.sub.CORE, higher N2.sub.R/L, and higher HSR, and, thus, making it more challenging to meet dynamics margins (e.g., Alford stability and/or third mode margin). A.sub.IN and A.sub.EX are proportional to engine core size. A.sub.IN increases to achieve higher HP compressor pressure ratios. AR is indicative of the HP compressor pressure ratio, and, thus, indicative of T25. Accordingly, embodiments 1 to 120 provide for lowering the core size, while accounting for the dynamics margins and overall engine performance.

(169) FIG. **10** represents, in graph form, the HSP.sub.AR as a function of the HSP.sub.X. HSP.sub.X is given by relationship (8) detailed above. HSP.sub.AR is in a range from 41 to 228 and HSP.sub.X is in a range from 3.8 in.sup.2 to 69.1 in.sup.2. An area **1000** represents the boundaries of HSP.sub.AR and HSP.sub.X. HSP.sub.AR is given by relationship (10) above. HSP.sub.AR and HSP.sub.X are bounded by an upper bound **1002**. The upper bound **1002** is given by (22):

$$HSP\text{.sub.AR} < \mathrm{MAX}(280-9*(HSP\text{.sub.X}),82-0.4*(HSP\text{.sub.X})) \qquad (22)$$

(170) With reference to TABLE 3 and FIG. **10**, in general, HSP.sub.AR increases as HSP.sub.X increases, and HSP.sub.AR decreases as HSP.sub.X increases. HSP.sub.X increases with increased A.sub.EX and/or increases OPR.sub.T/O, and decreases with increased FN.sub.T/O. In general, better engine performance, higher BPR, smaller engine core size, higher L.sub.CORE/D.sub.CORE, and higher T25 result in reduced dynamics margins. Higher AR, higher HP compressor pressure ratio, lower T25, and higher inlet corrected flow result in lower N2.sub.R/L. Increased radius ratio, reduced blade height, reduce HP compressor speeds, and lower HP compressor pressure ratios result in diminishing returns on dynamics margins with poor performance. Accordingly, embodiments 1 to 120 provide for balancing higher AR with increased radius ratios to meet dynamics margins with improved performance of the engine core (and of the overall engine).

(171) The lower the HSP.sub.AR, the greater the third mode margin and the lower the HP compressor tip radius ratio for improved performance of the HP compressor and the HP turbine. Thus, the HSP.sub.AR is selected for providing a balance among improving the third mode margin of the HP shaft, without overly sacrificing performance of the HP compressor and/or the HP turbine.

(172) FIG. **11** represents, in graph form, the HSP.sub.AR as a function of the HSP.sub.X, according to another embodiment. HSP.sub.X is given by relationship (8) detailed above. HSP.sub.AR is in a range from 41 to 228 and HSP.sub.X is in a range from 3.8 in.sup.2 to 69.1 in.sup.2. An area **1100** represents the boundaries of HSP.sub.AR and HSP.sub.x. HSP.sub.AR is bounded by an upper bound **1102**. The upper bound **1102** is given by (23):

(173) $HSP_{AR} < \frac{350}{(HSP_X - 4)^{0.5}}$ (23)

(174) With reference to TABLE 3 and FIG. **11**, in general, HSP.sub.AR increases as HSP.sub.X increases, and HSP.sub.AR decreases as HSP.sub.X increases, as detailed above. HSP.sub.X increases with increased A.sub.EX and/or increases OPR.sub.T/O, and decreases with increased FN.sub.T/O, as detailed above.

(175) TABLE 4 lists embodiments of the HP compressor and the HP shaft along with the associated HSP_A.sub.IN values of the HP compressor and the HP shaft. The embodiments inform the dimensions or qualities of the HP compressor and the HP shaft that are believed reasonable and practical for the HP compressor and the HP shaft for providing a balance among improving the third mode margin of the HP shaft, without overly reducing performance of the HP compressor and/or the HP turbine. In other words, the HSP_A.sub.IN indicates the operating range of interest, taking into account the constraints in which the HP compressor operates, e.g., the HP compressor inlet temperature and the HP compressor inlet corrected flow, that have not been previously considered in HP compressor and HP shaft designs, as detailed above.

(176) TABLE-US-00004 TABLE 4 FN.sub.T/O N2.sub.R/L R.sub.HUB,IN/ R.sub.TIP,IN R.sub.TIP,EX A.sub.IN A.sub.EX L.sub.CORE/ HSP.sub.X1 HSP_A.sub.IN Emb. (lbf) (RPM) R.sub.TIP,IN (in) (in) (in.sup.2) (in.sup.2) D.sub.CORE (in.sup.2/klbf) (in.sup.2) 1 35940 24788 0.47 8.35 6.9 170 21 3.4 0.6 3081 2 36228 23020 0.56 8.68 7.58 162 22 2.9 0.76 1927 3 36228 22481 0.47 8.85 7.86 192 22 2.9 0.62 2572 4 36228 22417 0.47 8.6 7.72 181 22 3 0.6 2565 5 36228 22246 0.56 8.9 7.8 171 23 2.8 0.8 1852 6 36228 20928 0.56 10.25 8.03 227 29 2.9 0.8 2828 7 36228 19967 0.56 11.2 8.41 270 32 2.8 0.73 3288 8 36228 21281 0.56 9.4 8.38 190 26 2.6 0.9 1841 9 36228 21695 0.56 9.1 8.01 178 25 2.8 0.84 1988 10 39515 19922 0.56 10.35 8.43 230 32 3 1.0 2970 11 39515 20809 0.57 10.25 8.76 223 34 2.7 1.36 2369 12 27633 20809 0.57 9.69 8.76 199 34 2.5 1.95 1729 13 19324 20809 0.57 9.69 8.76 199 34 2.3 2.79 1427 14 18124 35788 0.4 5.68 4.73 85 12 4.3 0.8 2683 15 12674 35788 0.4 5.68 4.73 85 12 4 1.15 2406 16 75161 12306 0.4 13.98 13.4 516 68 2.1 0.9 3665 17 107480 10580 0.4 16.32 15.83 703 95 2.1 0.88 5017 18 25247 24181 0.52 8.02 7.37 148 24 2.8 1.51 1645 19 25288 23523 0.56 8.76 7.62 165 26 2.7 1.6 1771 20 29198 18378 0.57 10.07 9.24 213 30 2.2 1.62 1444 21 26169 18401 0.58 9.96 9.2 207 34 2.3 2 1462 22 23249 21259 0.54 9.2 8.17 190 28 2.5 1.9 1726 23 29699 23255 0.47 8.37 7.43 172 22 2.8 0.92 2110 24 20081 20398 0.54 9.09 8.23 184 26 2.5 1.58 1628 25 27940 24432 0.56 8.23 7.35 145 19 2.8 0.84 1642 26 24574 19914 0.5 9.06 8.64 194 18 2.4 0.72 1641 27 28698 19790 0.55 9.55 8.49 201 19 2.4 0.67 1682 28 22111 24618 0.46 7.39 7.03 136 15 3 0.7 1819 29 24668 23073 0.53 8.45 7.52 162 16 2.7 0.65 1757 30 25477 24152 0.54 7.91 7.16 139 15 2.9 0.57 1682 31 26508 24437 0.57 8.16 7.23 141 13 2.8 0.51 1585 32 31781 23043 0.43 8.21 7.73 173 20 2.7 0.63 1981 33 29444 20310 0.46 9.13 8.61 207 29 2.5 1.52 1911 34 25868 23662 0.52 8.11 7.35 151 22 2.7 1.32 1656 35 25169 24039 0.44 7.6 7.43 147 18 2.8 0.9 1784 36 29459 20133 0.47 9.12 8.65 202 26 2.6 1.08 1998 37 30518 20410 0.51 9.72 8.69 219 22 2.7 0.73 2369 38 25749 22900 0.55 9.01 7.77 177 18 2.9 0.69 2191 39 18136 28164 0.54 6.89 5.8 106 11 3.6 0.63 2045 40 36229 25626 0.4 7.95 6.62 167 24 3.6 0.81 3841 41 36254 23225 0.4 8.53 7.19 192 23 3.3 0.64 3582 42 36253 21410 0.4 9.03 7.71 215 23 3.3 0.63 3912 43 52524 19521 0.54 10.46 8.59 243 34 2.8 0.81 2881 44 52523 18233 0.54 10.97 9.1 268 34 2.8 0.8 3166 45 52525 19710 0.6 10.6 8.54 226 36 2.6 0.84 2126 46 52561 18510 0.54 10.91 9 265 35 2.6 0.66 2596 47 52558 15207 0.54 12.48 10.69 347 34 2.5 0.64 3269 48 52560 17374 0.6 11.55 9.49 268 34 2.4 0.65 2161 49 52523 20022 0.4 9.99 8.94 263 34 2.7 0.81 3313 50 52524 19304 0.54 10.57 9.25 249 36 2.4 0.84 2063 51 52522 17220 0.54 11.4 10.2 289 34 2.4 0.81 2318 52 52523 18140 0.6 11.17 9.75 251 35 2.2 0.82 1707 53 52522 16123 0.6 12.09 10.81 294 33 2.2 0.79 1915 54 52560 18670 0.4 10.55 9.51 294 35 2.5 0.67 2953 55 52558 15873 0.4 11.82 10.98 369 34 2.3 0.66 3333 56 18124 27161 0.6 7.06 6.71 100 12 2.8 0.8 1038 57 18136 22208 0.54 8.26 8.27 152 12 2.4 0.67 1167 58 36228 24006 0.4 8.32 7.9 182 24 2.6 0.82 2057

59 36228 20495 0.54 9.56 9.1 203 24 2.3 0.83 1460   60 36228 17397 0.54 10.72 10.57 256 24 2.1 0.81 1584   61 36230 24405 0.6 8.66 7.84 151 27 2.3 0.91 1101   62 36253 18478 0.4 10.08 10.01 268 24 2.2 0.67 2020   63 52523 19700 0.4 10.12 9.62 270 36 2.3 0.84 2367   64 29791 20730 0.46 8.88 8.71 194 16 2.5 0.53 1743   65 38564 26513 0.45 7.87 7.08 156 21 3 0.86 2282   66 41861 20516 0.45 9.07 8.25 205 22 2.8 0.53 2578   67 34695 27440 0.45 7.51 6.66 142 19 3.1 0.66 2115   68 45080 22948 0.54 9.14 7.57 185 26 2.8 0.72 2172   69 38835 23902 0.53 8.55 7.78 165 19 2.7 0.78 1774   70 41411 23444 0.51 8.69 7.62 174 29 2.9 1.08 2137   71 40010 22409 0.54 8.53 8.29 161 18 2.4 0.57 1278   72 34589 26430 0.55 7.86 7.06 135 19 2.8 0.85 1464   73 36392 24926 0.48 8.02 6.74 155 18 3.2 0.5 2529   74 29097 24030 0.56 8.03 7.36 140 13 2.9 0.56 1637   75 29975 24497 0.45 7.56 7.08 143 13 3.1 0.44 2160   76 35983 25286 0.51 8.03 7.1 151 21 3 0.89 2098   77 35202 27176 0.45 7.58 6.94 143 26 2.9 1.14 1879   78 28834 24306 0.55 7.91 6.88 138 14 3.1 0.49 1877   79 38443 21613 0.55 8.83 8.52 171 20 2.4 0.66 1308   80 27754 27294 0.47 7.19 6.17 126 13 3.4 0.48 2321   81 27382 26052 0.42 7.46 6.35 144 15 3.6 0.56 3090   82 34118 26029 0.49 7.71 6.38 142 15 3.5 0.44 2798   83 41362 21762 0.53 8.96 7.99 182 17 2.7 0.4 1953   84 33372 24839 0.43 7.91 6.83 160 20 3.4 0.6 2966   85 44425 25546 0.43 8.17 6.96 172 28 3.1 0.77 2743   86 28190 23396 0.41 7.78 7.46 158 13 3 0.45 2321   87 35231 21419 0.53 8.98 8.12 182 15 2.7 0.42 1872   88 28272 26095 0.49 7.3 6.66 127 13 3.1 0.47 1829   89 42416 23364 0.41 8.43 7.63 186 17 2.9 0.4 2538   90 28346 24653 0.4 7.88 6.84 164 15 3.4 0.52 3179   91 43315 23589 0.45 8.86 7.21 196 27 3.3 0.77 3472   92 33540 20805 0.45 8.93 8.52 200 14 2.7 0.43 2150   93 42603 23344 0.44 8.82 7.39 198 26 3.2 0.76 3379   94 29583 26303 0.46 7.4 6.45 135 13 3.4 0.43 2515   95 31357 23050 0.56 8.55 7.57 158 15 2.7 0.49 1619   96 44345 23094 0.4 8.73 7.29 201 23 3.3 0.51 3681   97 36178 24334 0.41 8.11 6.89 172 17 3.4 0.46 3319   98 33158 24109 0.48 8.11 7.35 158 15 2.8 0.44 1921   99 32153 27525 0.41 6.94 6.61 125 14 3.1 0.43 1918 100 44003 26067 0.44 7.93 7.37 159 26 2.8 0.94 2012 101 42640 24924 0.51 8.56 6.89 171 27 3.1 0.79 2614 102 30510 25797 0.41 7.61 6.42 152 16 3.6 0.52 3318 103 39341 24704 0.41 8.26 6.9 178 22 3.4 0.69 3614 104 38354 26645 0.45 7.59 6.33 144 19 3.4 0.51 2666 105 39061 23578 0.49 8.39 7.01 168 16 3.3 0.4 2928 106 34146 27652 0.44 7.32 6.24 136 16 3.4 0.46 2507 107 44129 21015 0.44 9.29 7.9 219 25 3.1 0.56 3548 108 39281 24454 0.55 8.24 7.5 149 17 2.7 0.53 1523 109 27391 25294 0.53 7.5 7.19 126 14 2.8 0.63 1410 110 36428 24002 0.41 8.35 7.04 182 19 3.3 0.51 3434 111 45242 25956 0.43 7.81 6.65 156 20 3.2 0.45 2654 112 31468 23911 0.55 7.83 6.89 135 14 3.2 0.45 2063 113 44365 24993 0.49 8.52 6.97 174 27 3.1 0.75 2585 114 40875 24106 0.5 8.51 7.74 171 20 2.8 0.78 1929 115 38425 26699 0.4 7.62 6.8 153 21 3.1 0.68 2503 116 42939 24229 0.44 8.37 7.6 178 21 2.9 0.78 2435 117 38881 21483 0.48 8.96 8.52 194 20 2.6 0.65 1900 118 43139 23965 0.43 8.39 7.28 181 21 3 0.49 2763 119 36707 26550 0.45 7.54 7.18 143 23 2.9 0.96 1793 120 43047 24214 0.42 8.39 7.18 182 23 3.1 0.53 2828

(177) The embodiments 1 to 120 of TABLE 4 are the same as the embodiments 1 to 120 of TABLES 1 to 3, but TABLE 4 includes parameters in the HSP_A.sub.IN relationship (12) above. The ranges of FN.sub.T/O, N2.sub.R/L, OPR.sub.T/O, R.sub.HUB,IN/R.sub.TIP,IN, R.sub.TIP,IN, R.sub.TIP,EX, R.sub.HUB,EX, A.sub.IN, A.sub.EX, and L.sub.CORE/D.sub.CORE are detailed above. In general, lower FN.sub.T/O, higher EGT, and/or higher OPR.sub.T/O results in lower core size (e.g., lower L.sub.CORE and lower D.sub.CORE), but higher L.sub.CORE/D.sub.CORE, higher N2R/L, and higher HSR, and, thus, making it more challenging to meet dynamics margins (e.g., Alford stability and/or third mode margin). A.sub.IN and A.sub.EX is proportional to the engine core size. A.sub.IN is indicative of the HP compressor inlet corrected flow and the HP compressor pressure ratio, and, thus, indicative of T25. Accordingly, embodiments 1 to 120 provide for lowering the core size, while accounting for the dynamics margins and overall engine performance.

(178) FIG. **12** represents, in graph form, the HSP_A.sub.IN as a function of the HSP.sub.X1. HSP.sub.X1 is given by relationship (13) detailed above. HSP_A.sub.IN is in a range from 1038 in.sup.2 to 5017 in.sup.2, and HSP.sub.X1 is in a range from 0.4 in.sup.2/k-lbf to 2.79 in.sup.2/k-

lbf. In some embodiments, HSP_A.sub.IN is in a range from 1,420 in.sup.2 to 3,920 in.sup.2. An area **1200** represents the boundaries of HSP_A.sub.IN and HSP.sub.X1. HSP_A.sub.IN and HSP.sub.X1 are bounded by an upper bound **1202**. The upper bound **1202** is given by the relationship (24):

(179) $$HSP\_A_{IN} < MAX\left(\frac{4200}{(HSP_{X_1})^{1.5}}, 2850 - 500 * (HSP_{X_1})\right) \quad (24)$$

(180) With reference to TABLE 4 and FIG. **12**, in general, HSP_A.sub.IN increases as HSP.sub.X1 increases, and HSP_A.sub.IN decreases as HSP.sub.X1 increases. HSP.sub.X1 increases with increased A.sub.EX, and decreases with increased FN.sub.T/O. In general, better engine performance, higher BPR, smaller engine core size, higher L.sub.CORE/D.sub.CORE, and higher T25 result in reduced dynamics margins. Higher AR, higher HP compressor pressure ratio, lower T25, and higher inlet corrected flow result in lower N2.sub.R/L. Increased radius ratio, reduced blade height, reduce HP compressor speeds, and lower HP compressor pressure ratios result in diminishing returns on dynamics margins with poor performance. Accordingly, embodiments 1 to 120 provide for balancing higher A.sub.IN with increased radius ratios to meet dynamics margins with improved performance of the engine core (and of the overall engine).

(181) The lower the HSP_A.sub.IN, the greater the third mode margin and the lower the HP compressor tip radius ratio for improved performance of the HP compressor and the HP turbine. Thus, the HSP_A.sub.IN is selected for providing a balance among improving the third mode margin of the HP shaft, without overly sacrificing performance of the HP compressor and/or the HP turbine.

(182) TABLE 5 lists embodiments of the HP compressor and HP shaft along with the associated HSP_U.sub.RIM,R/L values of the HP compressor and the HP shaft. The embodiments inform of the dimensions or qualities of the HP compressor and the HP shaft that are believed reasonable and practical for the HP compressor and the HP shaft for providing a balance among improving the third mode margin of the HP shaft, without overly reducing performance of the HP compressor and/or the HP turbine. In other words, the HSP_U.sub.RIM,R/L indicates the operating range of interest, taking into account the constraints in which the HP compressor operates, e.g., the HP compressor inlet temperature and the HP compressor inlet corrected flow, that have not been previously considered in HP compressor and HP shaft designs, as detailed above.

(183) TABLE-US-00005 TABLE 5 N2.sub.R/L T.sub.IC T25.sub.T/O T3.sub.T/O HSP.sub.X A.sub.F,IN U.sub.RIM,R/L HSP_U.sub.RIM,R/L Emb. (RPM) OPR.sub.T/O (° R) N.sub.Stg AR (° R) (° R) (in.sup.2) (in.sup.2) (ft/s) (in.sup.−2/3(ft/s/° R).sup.−3 1 24788 49.5 0 10 7.9 747 1881 9.3 219 1382 0.48 2 23020 44.1 0 9 7.3 745 1818 10.8 236 1426 0.31 3 22481 41.8 0 10 8.6 690 1788 8.5 246 1450 0.26 4 22417 40.7 0 10 8.4 690 1774 7.7 232 1420 0.29 5 22246 44.1 0 9 7.3 745 1818 12.2 249 1419 0.28 6 20928 44.1 0 10 7.8 725 1818 15.1 330 1357 0.29 7 19967 44.1 0 11 8.5 702 1818 15 394 1356 0.24 8 21281 44.1 0 9 7.2 749 1818 15.5 278 1460 0.23 9 21695 44.1 0 9 7.2 749 1818 13.5 260 1420 0.29 10 19922 44.1 0 9 7.2 748 1818 20.6 337 1356 0.34 11 20809 44.1 0 8 6.5 780 1818 30.4 330 1473 0.25 12 20809 37.4 0 8 5.8 777 1729 36.9 295 1473 0.19 13 20809 31.7 0 8 5.8 740 1646 44.7 295 1473 0.13 14 35788 40.9 0 9 7.2 730 1776 5.7 101 1347 1 15 35788 34.6 0 9 7.2 695 1690 6.9 101 1347 0.77 16 12306 47.8 −100 10 7.6 651 1614 43 614 1350 0.09 17 10580 56.4 −100 10 7.4 696 1711 69.1 837 1371 0.09 18 24181 44.9 −71 8 6.1 735 1667 24.2 202 1441 0.25 19 23523 41.7 −3 8 6.4 770 1781 25.4 241 1449 0.28 20 18378 32.5 −59 8 7.1 629 1515 23.4 319 1395 0.12 21 18401 26.3 −7 8 6.2 673 1539 26 312 1380 0.13 22 21259 32.5 −18 8 6.7 684 1615 25.7 266 1409 0.18 23 23255 53.5 −98 9 7.7 673 1680 16.2 220 1408 0.25 24 20398 32.5 −6 9 7.1 679 1644 19.5 259 1374 0.18 25 24432 62.9 −54 9 7.6 760 1886 14.8 213 1477 0.31 26 19914 53.5 −80 10 10.9 600 1698 10.1 258 1443 0.15 27 19790 53.4 −66 10 10.4 625 1742 10.2 287 1402 0.17 28 24618 53.5 −66 10 8.8 668 1752 8.4 171 1433 0.29 29 23073 62.9 −63 10 10.1 671 1848 9.7 224 1444 0.26 30 24152 62.9 −70 10 9.6 678 1832 7.6 197 1439 0.3 31 24437 82 −93 10 10.5 690 1929 8.1 209

1478 0.3 32 23043 62.9 −60 10 8.6 717 1866 11.7 212 1468 0.25 33 20310 34.9 −98 8 7.2 598 1455 22.3 262 1429 0.12 34 23662 40.6 −93 8 6.9 650 1551 17.3 206 1416 0.21 35 24039 51.2 −98 9 8 654 1652 12.5 182 1474 0.22 36 20133 43 −58 9 7.8 661 1657 17.7 261 1434 0.18 37 20410 58.8 −14 10 9.9 711 1944 13.9 297 1474 0.25 38 22900 64.6 −6 10 10 737 2020 11.6 255 1478 0.34 39 28164 40.6 0 10 9.2 665 1773 4.3 149 1347 0.56 40 25626 40.7 0 9 7.1 736 1774 11.4 199 1348 0.58 41 23225 40.6 0 10 8.3 691 1772 8.8 229 1350 0.4 42 21410 40.4 0 10 9.4 660 1770 8.6 256 1350 0.38 43 19521 40.7 0 9 7.1 735 1774 16.5 344 1350 0.28 44 18233 41 0 9 7.8 709 1778 16.6 378 1350 0.28 45 19710 40.1 0 9 6.3 766 1766 17.7 353 1350 0.23 46 18510 40.7 0 10 7.6 716 1774 13.9 374 1350 0.21 47 15207 40.1 0 10 10.3 636 1766 12.7 489 1350 0.18 48 17374 40.6 0 10 7.9 705 1773 13.1 419 1350 0.17 49 20022 40.8 0 9 7.6 715 1776 16.8 313 1450 0.23 50 19304 40.8 0 9 6.9 742 1776 18.2 351 1450 0.17 51 17220 40.9 0 9 8.4 689 1777 16.7 408 1450 0.15 52 18140 40.8 0 9 7.2 730 1775 17.1 392 1450 0.14 53 16123 40.8 0 9 8.8 678 1775 15.8 459 1450 0.13 54 18670 40.7 0 10 8.4 690 1774 14 350 1450 0.16 55 15873 39.9 0 10 10.7 627 1764 13.3 439 1450 0.13 56 27161 40.8 0 9 8.5 687 1776 5.7 156 1523 0.26 57 22208 39.4 0 10 12.5 591 1757 4.7 214 1557 0.14 58 24006 40.9 0 9 7.6 717 1776 11.8 217 1550 0.19 59 20495 41 0 9 8.4 691 1778 12.1 287 1550 0.13 60 17397 40.2 0 9 10.8 627 1767 11.4 361 1550 0.1 61 24405 40.1 0 9 5.6 803 1766 14.4 236 1550 0.14 62 18478 39.8 0 10 11 620 1762 9.5 319 1550 0.1 63 19700 40.9 0 9 7.6 717 1778 17.9 322 1550 0.13 64 20730 46.7 0 10 12.4 599 1774 5.6 248 1523 0.15 65 26513 48.5 0 8 7.3 739 1809 13 195 1523 0.34 66 20516 39.3 0 10 9.3 656 1756 6.7 259 1399 0.25 67 27440 40.3 −25 9 7.6 714 1769 7.4 177 1484 0.32 68 22948 40.2 −25 9 7.1 733 1768 11.1 262 1401 0.27 69 23902 42.3 0 8 8.5 693 1795 9.4 230 1538 0.24 70 23444 39.3 0 8 6.1 771 1755 17.7 237 1432 0.31 71 22409 44.2 0 9 8.7 670 1753 6.8 228 1550 0.15 72 26430 40.1 0 8 7.1 730 1766 9.5 194 1527 0.26 73 24926 45.2 0 10 8.4 685 1767 6.1 202 1369 0.38 74 24030 46.7 −25 9 10.6 634 1779 5.1 203 1482 0.27 75 24497 47.3 0 10 10.9 630 1786 4 180 1448 0.33 76 25286 38.4 −25 8 7.4 711 1743 10.3 203 1461 0.34 77 27176 39.2 −25 8 5.6 801 1754 16.8 181 1501 0.3 78 24306 42.3 −25 10 9.8 633 1726 4.2 197 1388 0.31 79 21613 38.2 0 9 8.4 676 1740 7.5 245 1534 0.14 80 27294 43.6 0 10 9.5 647 1744 4.1 162 1385 0.43 81 26052 43.3 −25 10 9.5 646 1740 5.4 175 1355 0.49 82 26029 48.9 0 10 9.4 674 1808 4.8 187 1360 0.52 83 21762 48.9 −25 10 10.9 637 1804 4.9 252 1452 0.22 84 24839 44.3 −25 10 8 720 1820 7.9 197 1376 0.45 85 25546 43.2 −25 9 6.2 763 1749 13.4 210 1403 0.35 86 23396 45.3 −25 10 12.4 593 1758 3.8 190 1468 0.28 87 21419 47.9 0 10 12.4 605 1789 4.3 253 1463 0.21 88 26095 44.8 −25 10 9.6 651 1759 4.1 167 1443 0.32 89 23364 48.5 −25 10 10.9 635 1799 4.9 223 1481 0.24 90 24653 40 −25 10 11.1 620 1766 4.5 195 1396 0.4 91 23589 41.3 −25 9 7.3 731 1782 12.5 247 1356 0.43 92 20805 47.8 −25 10 13.9 579 1784 4.3 251 1497 0.19 93 23344 41.4 0 9 7.6 721 1783 12.1 244 1386 0.39 94 26303 47.6 0 10 10.7 637 1790 3.8 172 1407 0.44 95 23050 41.7 −25 10 10.2 646 1787 4.7 230 1456 0.22 96 23094 42.4 0 10 8.9 683 1796 7.2 239 1367 0.39 97 24334 45.9 −25 10 10.3 637 1770 5.2 206 1380 0.41 98 24109 46 0 10 10.8 627 1770 4.4 207 1477 0.23 99 27525 48.7 0 10 9 683 1806 4.3 151 1505 0.31 100 26067 48.4 −25 8 6 801 1813 17.6 197 1541 0.28 101 24924 41.3 −25 9 6.3 776 1782 13.1 230 1354 0.4 102 25797 39.3 −25 10 9.6 648 1756 4.7 182 1355 0.49 103 24704 43.8 −25 9 8.1 688 1751 9.7 214 1374 0.46 104 26645 43.6 0 10 7.4 713 1750 6.3 181 1355 0.43 105 23578 48.7 0 10 10.6 643 1803 4.6 221 1367 0.43 106 27652 45.3 −25 10 8.6 680 1768 4.9 168 1406 0.41 107 21015 42.1 −25 10 8.9 682 1793 8.5 271 1354 0.35 108 24454 47.1 −25 9 8.9 679 1788 6.1 213 1523 0.22 109 25294 45 −25 9 9.1 665 1763 5.8 177 1517 0.25 110 24002 43.8 0 10 9.7 667 1814 6.2 219 1384 0.42 111 25956 44.8 −25 10 7.6 710 1764 6.1 191 1392 0.36 112 23911 46.1 −25 10 9.6 654 1774 4.2 193 1368 0.4 113 24993 44.5 0 9 6.5 758 1764 13.1 228 1379 0.36 114 24106 46.7 −25 8 8.4 694 1784 11 228 1537 0.24 115 26699 40.3 −25 9 7.2 728 1769 8.6 182 1463 0.34 116 24229 44.4 −25 8 8.3 685 1757 10.8 220 1510 0.28 117 21483 46.8 −25 9 9.5 662 1783 9.1 252 1524 0.19 118 23965 43.5 0 10 8.7 695 1810 6.5 221 1423 0.32 119 26550 40.8 −25 8 6.3 770 1776 13 179 1542 0.28 120 24214 42.7 −25 10 7.9 715 1799 7.7 221 1404 0.32

(184) The embodiments 1 to 120 of TABLE 5 are the same as the embodiments 1 to 120 of TABLES 1 to 4, but TABLE 5 includes parameters in the HSP_U.sub.RIM,R/L relationship (14) above. The ranges of N2.sub.R/L, OPR.sub.T/O, T.sub.IC, N.sub.STG, A.sub.IN, A.sub.EX, AR, T25.sub.T/O, T3.sub.T/O, L.sub.CORE/D.sub.CORE, A.sub.F,IN, and U.sub.RIM,R/L are detailed above. In general, lower FN.sub.T/O, higher EGT, and/or higher OPR.sub.T/O results in lower core size (e.g., lower L.sub.CORE and lower D.sub.CORE), but higher L.sub.CORE/D.sub.CORE, higher N2.sub.R/L, and higher HSR, and, thus, making it more challenging to meet dynamics margins (e.g., Alford stability and/or third mode margin). A.sub.IN and A.sub.EX is proportional to the engine core size. A.sub.IN is indicative of the HP compressor inlet corrected flow and the HP compressor pressure ratio, and, thus, indicative of T25. AR is indictive of the HP compressor pressure ratio (e.g., indicative of T25). U.sub.RIM,R/L is indicative of the HP compressor exit hub radius and N2.sub.R/L. A.sub.F,IN and T3.sub.T/O are indicative of the HP compressor inlet temperature and the corrected flow. Accordingly, embodiments 1 to 120 provide for lowering the core size, while accounting for the dynamics margins and overall engine performance.

(185) FIG. **13** represents, in graph form, the HSP_U.sub.RIM,R/L as a function of the HSP.sub.X. HSP.sub.X is given by relationship (8) detailed above. HSP_U.sub.RIM,R/L is in a range from 0.09 in.sup.−2/3 (ft/s/° R).sup.−3 to 1.00 in.sup.−2/3 (ft/s/° R).sup.−3, and HSP.sub.X is in a range from 3.8 in.sup.2 to 69.1 in.sup.2. An area **1300** represents the boundaries of HSP_U.sub.RIM,R/L and HSP.sub.X. HSP_U.sub.RIM,R/L and HSP.sub.X are bounded by an upper bound **1302**. The upper bound **1302** is given by (25):

(186) $HSP\_U_{RIM,R/L} < \frac{6.6}{(HSP_X)}$ (25)

(187) With reference to TABLE 5 and FIG. **13**, in general, HSP_U.sub.RIM,R/L increases as HSP.sub.X increases, and HSP_U.sub.RIM,R/L decreases as HSP.sub.X increases. HSP.sub.X increases with increased A.sub.EX, increased OPR.sub.T/O, and decreases with increased FN.sub.T/O. In general, better engine performance, higher BPR, smaller engine core size, higher L.sub.CORE/D.sub.CORE, and higher T25 result in reduced dynamics margins. Higher Aux, greater amount of HP compressor stages, higher HP compressor pressure ratio, lower T25, and higher inlet corrected flow result in lower N2.sub.R/L. Higher U.sub.RIM,R/L and reduced blade height, or increased HP compressor speeds, and lower HP compressor pressure ratios result in improved dynamics margin with marginal performance penalties. Accordingly, embodiments 1 to 120 provide for balancing higher N.sub.STG and A.sub.F,IN with increased radius ratios to meet dynamics margins with improved performance of the engine core (and of the overall engine).

(188) The lower the HSP_U.sub.RIM,R/L, the greater the third mode margin and the higher T3 (OPR capability) for performance. Thus, the HSP_U.sub.RIM,R/L is selected for providing a balance among improving the third mode margin of the HP shaft, without overly reducing performance of the HP compressor and/or the HP turbine.

(189) FIG. **14** represents, in graph form, the HSP_U.sub.RIM,R/L as a function of the HSP.sub.X, according to another embodiment. HSP.sub.X is given by relationship (5) detailed above. HSP_U.sub.RIM,R/L is in a range from 0.09 in.sup.−2/3 (ft/s/° R).sup.−3 to 1.00 in.sup.−2/3 (ft/s/° R).sup.−3, and HSP.sub.X is in a range from 3.8 in.sup.2 to 69.1 in.sup.2. An area **1400** represents the boundaries of HSP_U.sub.RIM,R/L and HSP.sub.X. HSP_U.sub.RIM,R/L and HSP.sub.X are bounded by an upper bound **1402**. The upper bound **1402** is given by (26):

(190) $HSP\_U_{RIM,R/L} < \frac{2.9}{HSP_X^{0.75}}$ (26)

(191) With reference to TABLE 5 and FIG. **14**, in general, HSP_U.sub.RIM,R/L increases as HSP.sub.X increases, and HSP_U.sub.RIM,R/L decreases as HSP.sub.X increases, as detailed above. HSP.sub.X increases with increased A.sub.EX, increased OPR.sub.T/O, and decreases with increased FN.sub.T/O, as detailed above.

(192) TABLE 6 lists embodiments of the HP compressor and the HP shaft along with the associated HSP.sub.RR values of the HP compressor and the HP shaft. The embodiments inform of the

dimensions or qualities of the HP compressor and the HP shaft that are believed reasonable and practical for the HP compressor and the HP shaft for providing a balance among improving the third mode margin of the HP shaft, without overly reducing performance of the HP compressor and/or the HP turbine. In other words, the HSP.sub.RR indicates the operating range of interest, taking into account the constraints in which the HP compressor operates, e.g., the HP compressor inlet temperature and the HP compressor inlet corrected flow, that have not been previously considered in HP compressor and HP shaft designs, as detailed above.

(193) TABLE-US-00006 TABLE 6 T.sub.IC R.sub.HUB,IN/ R.sub.TIP,IN R.sub.TIP,EX T25.sub.T/O HSP.sub.X Emb. OPR.sub.T/O (° R) N.sub.Stg R.sub.TIP,IN (in) (in) AR (° R) (in.sup.2) HSP.sub.RR 1 49.5 0 10 0.47 8.35 6.9 7.9 747 9.3 37.6 2 44.1 0 9 0.56 8.68 7.58 7.3 745 10.8 24.6 3 41.8 0 10 0.47 8.85 7.86 8.6 690 8.5 23.7 4 40.7 0 10 0.47 8.6 7.72 8.4 690 7.7 25 5 44.1 0 9 0.56 8.9 7.8 7.3 745 12.2 22.4 6 44.1 0 10 0.56 10.25 8.03 7.8 725 15.1 24.4 7 44.1 0 11 0.56 11.2 8.41 8.5 702 15 22.3 8 44.1 0 9 0.56 9.4 8.38 7.2 749 15.5 20.3 9 44.1 0 9 0.56 9.1 8.01 7.2 749 13.5 23.3 10 44.1 0 9 0.56 10.35 8.43 7.2 748 20.6 26.8 11 44.1 0 8 0.57 10.25 8.76 6.5 780 30.4 24 12 37.4 0 8 0.57 9.69 8.76 5.8 777 36.9 19.5 13 31.7 0 8 0.57 9.69 8.76 5.8 740 44.7 14.6 14 40.9 0 9 0.4 5.68 4.73 7.2 730 5.7 62.5 15 34.6 0 9 0.4 5.68 4.73 7.2 695 6.9 50.7 16 47.8 −100 10 0.4 13.98 13.4 7.6 651 43 11.2 17 56.4 −100 10 0.4 16.32 15.83 7.4 696 69.1 12.9 18 44.9 −71 8 0.52 8.02 7.37 6.1 735 24.2 22.4 19 41.7 −3 8 0.56 8.76 7.62 6.4 770 25.4 23.6 20 32.5 −59 8 0.57 10.07 9.24 7.1 629 23.4 9.9 21 26.3 −7 8 0.58 9.96 9.2 6.2 673 26 11.9 22 32.5 −18 8 0.54 9.2 8.17 6.7 684 25.7 15.8 23 53.5 −98 9 0.47 8.37 7.43 7.7 673 16.2 20.6 24 32.5 −6 9 0.54 9.09 8.23 7.1 679 19.5 15.1 25 62.9 −54 9 0.56 8.23 7.35 7.6 760 14.8 24.4 26 53.5 −80 10 0.5 9.06 8.64 10.9 600 10.1 11.3 27 53.4 −66 10 0.55 9.55 8.49 10.4 625 10.2 12.1 28 53.5 −66 10 0.46 7.39 7.03 8.8 668 8.4 22.2 29 62.9 −63 10 0.53 8.45 7.52 10.1 671 9.7 18.2 30 62.9 −70 10 0.54 7.91 7.16 9.6 678 7.6 20.7 31 82 −93 10 0.57 8.16 7.23 10.5 690 8.1 19.9 32 62.9 −60 10 0.43 8.21 7.73 8.6 717 11.7 21.9 33 34.9 −98 8 0.46 9.13 8.61 7.2 598 22.3 12.3 34 40.6 −93 8 0.52 8.11 7.35 6.9 650 17.3 17.2 35 51.2 −98 9 0.44 7.6 7.43 8 654 12.5 19.3 36 43 −58 9 0.47 9.12 8.65 7.8 661 17.7 16 37 58.8 −14 10 0.51 9.72 8.69 9.9 711 13.9 20.3 38 64.6 −6 10 0.55 9.01 7.77 10 737 11.6 24.9 39 40.6 0 10 0.54 6.89 5.8 9.2 665 4.3 31.8 40 40.7 0 9 0.4 7.95 6.62 7.1 736 11.4 46.3 41 40.6 0 10 0.4 8.53 7.19 8.3 69 8.8 33.1 42 40.4 0 10 0.4 9.03 7.71 9.4 660 8.6 29.4 43 40.7 0 9 0.54 10.46 8.59 7.1 735 16.5 23.7 44 41 0 9 0.54 10.97 9.1 7.8 709 16.6 22 45 40.1 0 9 0.6 10.6 8.54 6.3 766 17.7 20.5 46 40.7 0 10 0.54 10.91 9 7.6 716 13.9 18.7 47 40.1 0 10 0.54 12.48 10.69 10.3 636 12.7 14.2 48 40.6 0 10 0.6 11.55 9.49 7.9 705 13.1 14.9 49 40.8 0 9 0.4 9.99 8.94 7.6 715 16.8 23.9 50 40.8 0 9 0.54 10.57 9.25 6.9 742 18.2 17 51 40.9 0 9 0.54 11.4 10.2 8.4 689 16.7 14.1 52 40.8 0 9 0.6 11.17 9.75 7.2 730 17.1 13.5 53 40.8 0 9 0.6 12.09 10.81 8.8 678 15.8 11.1 54 40.7 0 10 0.4 10.55 9.51 8.4 690 14 17.8 55 39.9 0 10 0.4 11.82 10.98 10.7 627 13.3 13.2 56 40.8 0 9 0.6 7.06 6.71 8.5 687 5.7 18.2 57 39.4 0 10 0.54 8.26 8.27 12.5 591 4.7 10 58 40.9 0 9 0.4 8.32 7.9 7.6 717 11.8 21.5 59 41 0 9 0.54 9.56 9.1 8.4 691 12.1 12.7 60 40.2 0 9 0.54 10.72 10.57 10.8 627 11.4 9.1 61 40.1 0 9 0.6 8.66 7.84 5.6 803 14.4 17.5 62 39.8 0 10 0.4 10.08 10.01 11 620 9.5 10.8 63 40.9 0 9 0.4 10.12 9.62 7.6 717 17.9 16.7 64 46.7 0 10 0.46 8.88 8.71 12.4 599 5.6 12 65 48.5 0 8 0.45 7.87 7.08 7.3 739 13 29.7 66 39.3 0 10 0.45 9.07 8.25 9.3 656 6.7 20.1 67 40.3 −25 9 0.45 7.51 6.66 7.6 714 7.4 28.3 68 40.2 −25 9 0.54 9.14 7.57 7.1 733 11.1 23.5 69 42.3 0 8 0.53 8.55 7.78 8.5 693 9.4 19.2 70 39.3 0 8 0.51 8.69 7.62 6.1 771 17.7 27.1 71 44.2 0 9 0.54 8.53 8.29 8.7 670 6.8 13.3 72 40.1 0 8 0.55 7.86 7.06 7.1 730 9.5 21.5 73 45.2 0 10 0.48 8.02 6.74 8.4 685 6.1 28.5 74 46.7 −25 9 0.56 8.03 7.36 10.6 634 5.1 17.5 75 47.3 0 10 0.45 7.56 7.08 10.9 630 4 22.3 76 38.4 −25 8 0.51 8.03 7.1 7.4 711 10.3 26.1 77 39.2 −25 8 0.45 7.58 6.94 5.6 801 16.8 31.2 78 42.3 −25 10 0.55 7.91 6.88 9.8 633 4.2 20.4 79 38.2 0 9 0.55 8.83 8.52 8.4 676 7.5 13 80 43.6 0 10 0.47 7.19 6.17 9.5 647 4.1 28.8 81 43.3 −25 10 0.42 7.46 6.35 9.5 646 5.4 33.3 82 48.9 0 10 0.49 7.71 6.38 9.4 674 4.8 33.3 83 48.9 −25 10 0.53 8.96 7.99 10.9 637 4.9 16.2 84 44.3 −25 10 0.43 7.91 6.83 8 720 7.9 35.8 85 43.2 −25 9 0.43 8.17 6.96 6.2 763 13.4 34.6 86 45.3 −25 10

0.41 7.78 7.46 12.4 593 3.8 19.2 87 47.9 0 10 0.53 8.98 8.12 12.4 605 4.3 14 88 44.8 −25 10 0.49 7.3 6.66 9.6 651 4.1 22.7 89 48.5 −25 10 0.41 8.43 7.63 10.9 635 4.9 20.4 90 40 −25 10 0.4 7.88 6.84 11.1 620 4.5 27.8 91 41.3 −25 9 0.45 8.86 7.21 7.3 731 12.5 35.3 92 47.8 −25 10 0.45 8.93 8.52 13.9 579 4.3 13.4 93 41.4 0 9 0.44 8.82 7.39 7.6 721 12.1 33 94 47.6 0 10 0.46 7.4 6.45 10.7 637 3.8 28.1 95 41.7 −25 10 0.56 8.55 7.57 10.2 646 4.7 15.9 96 42.4 0 10 0.4 8.73 7.29 8.9 683 7.2 31.8 97 45.9 −25 10 0.41 8.11 6.89 10.3 637 5.2 29.2 98 46 0 10 0.48 8.11 7.35 10.8 627 4.4 17.7 99 48.7 0 10 0.41 6.94 6.61 9 683 4.3 26.5 100 48.4 −25 8 0.44 7.93 7.37 6 801 17.6 30.1 101 41.3 −25 9 0.51 8.56 6.89 6.3 776 13.1 34.2 102 39.3 −25 10 0.41 7.61 6.42 9.6 648 4.7 34.2 103 43.8 −25 9 0.41 8.26 6.9 8.1 688 9.7 35.7 104 43.6 0 10 0.45 7.59 6.33 7.4 713 6.3 35 105 48.7 0 10 0.49 8.39 7.01 10.6 643 4.6 26.9 106 45.3 −25 10 0.44 7.32 6.24 8.6 680 4.9 31.7 107 42.1 −25 10 0.44 9.29 7.9 8.9 682 8.5 28 108 47.1 −25 9 0.55 8.24 7.5 8.9 679 6.1 17.5 109 45 −25 9 0.53 7.5 7.19 9.1 665 5.8 18.4 110 43.8 0 10 0.41 8.35 7.04 9.7 667 6.2 31.3 111 44.8 −25 10 0.43 7.81 6.65 7.6 710 6.1 31.9 112 46.1 −25 10 0.55 7.83 6.89 9.6 654 4.2 24.3 113 44.5 0 9 0.49 8.52 6.97 6.5 758 13.1 31.7 114 46.7 −25 8 0.5 8.51 7.74 8.4 694 11 20.2 115 40.3 −25 9 0.4 7.62 6.8 7.2 728 8.6 32.2 116 44.4 −25 8 0.44 8.37 7.6 8.3 685 10.8 23.9 117 46.8 −25 9 0.48 8.96 8.52 9.5 662 9.1 15.9 118 43.5 0 10 0.43 8.39 7.28 8.7 695 6.5 27.4 119 40.8 −25 8 0.45 7.54 7.18 6.3 770 13 27.6 120 42.7 −25 10 0.42 8.39 7.18 7.9 715 7.7 29.5

(194) The embodiments 1 to 120 of TABLE 6 are the same as the embodiments 1 to 120 of TABLES 1 to 5, but TABLE 6 includes parameters in the HSP.sub.RR relationship (19) above. The ranges of OPR.sub.T/O, T.sub.IC, R.sub.HUB,IN/R.sub.TIP,IN, R.sub.TIP,IN, R.sub.HUB,EX, A.sub.IN, A.sub.EX, AR, T25.sub.T/O, and L.sub.CORE/D.sub.CORE are detailed above. In general, lower FN.sub.T/O, higher EGT, and/or higher OPR.sub.T/O results in lower core size (e.g., lower L.sub.CORE and lower D.sub.CORE), but higher L.sub.CORE/D.sub.CORE, higher N2.sub.R/L, and higher HSR, and, thus, making it more challenging to meet dynamics margins (e.g., Alford stability and/or third mode margin). A.sub.IN and A.sub.EX are proportional to the engine core size. A.sub.IN is larger for higher HP compressor pressure ratios. The inlet radius ratio is indicative of the HP shaft speed. The exit radius ratio is indicative of the HP compressor pressure ratio and T25. Accordingly, embodiments 1 to 120 provide for lowering the core size, while accounting for the dynamics margins and overall engine performance.

(195) FIG. **15** represents, in graph form, the HSP.sub.RR as a function of the HSP.sub.X. HSP.sub.X is given by relationship (8) detailed above. HSP.sub.RR is in a range from 9.1 to 62.5, and HSP.sub.X is in a range from 3.8 in.sup.2 to 69.1 in.sup.2. An area **1500** represents the boundaries of HSP.sub.RR and HSP.sub.X. HSP.sub.RR and HSP.sub.X are bounded by an upper bound **1502**. The upper bound **1502** is given by (27):

$$HSP\text{.sub.RR}<\text{MAX}(77-2.6*(HSP\text{.sub.x}),27-0.2*(HSP\text{.sub.x})) \qquad (27)$$

(196) With reference to TABLE 6 and FIG. **15**, in general, HSP.sub.RR increases as HSP.sub.X increases, and HSP.sub.RR decreases as HSP.sub.X increases. HSP.sub.X increases with increased A.sub.EX, increased OPR.sub.T/O, and decreases with increased FN.sub.T/O. In general, better engine performance, higher BPR, smaller engine core size, higher L.sub.CORE/D.sub.CORE, and higher T25 result in reduced dynamics margins. Lower T25 and lower N2.sub.R/L result in higher HP compressor pressure ratio with similar work input. Increased radius ratio, reduced blade height, or reduced HP compressor speeds, and lower HP compressor pressure ratios result in diminishing returns on dynamics margin with poorer performance. Accordingly, embodiments 1 to 120 provide for balancing lower T25 with increased radius ratios to meet dynamics margins with improved performance of the engine core (and of the overall engine).

(197) The lower the HSP.sub.RR, the greater the third mode margin and the lower the HP compressor tip radius ratio for improved performance of the HP compressor and the HP turbine. Thus, the HSP.sub.RR is selected for providing a balance among improving the third mode margin of the HP shaft, without overly sacrificing performance of the HP compressor and/or the HP turbine.

(198) FIG. **16** represents, in graph form, the HSP.sub.RR as a function of the HSP.sub.X, according to another embodiment. HSP.sub.X is given by relationship (8) detailed above. HSP.sub.RR is in a range from 9.1 to 62.5, and HSP.sub.X is in a range from 3.8 in.sup.2 to 69.1 in.sup.2. An area **1600** represents the boundaries of HSP.sub.RR and HSP.sub.X. HSP.sub.RR and HSP.sub.X are bounded by an upper bound **1602**. The upper bound **1602** is given by (28):

(199) $HSP_{RR} < \frac{165}{HSP_X^{0.6}}$ (28)

(200) With reference to TABLE 6 and FIG. **16**, in general, HSP.sub.RR increases as HSP.sub.X increases, and HSP.sub.RR decreases as HSP.sub.X increases, as detailed above. HSP.sub.X increases with increased A.sub.EX, increased OPR.sub.T/O, and decreases with increased FN.sub.T/O, as detailed above.

(201) Further aspects are provided by the subject matter of the following clauses.

(202) A turbomachine engine comprises an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, the engine core having a length (L.sub.CORE), and the high-pressure compressor having an exit stage diameter (D.sub.CORE), and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and a ratio of L.sub.CORE/D.sub.CORE is from 2.1 to 4.3.

(203) The turbomachine engine of the preceding clause, an exhaust gas temperature of the turbomachine engine at redline speeds of the high-pressure shaft being from 1,063° C. to 1,282° C.

(204) The turbomachine engine of any preceding clause, a bypass ratio of the turbomachine engine being greater than 8.0, greater than 10.0, or greater than 12.0.

(205) The turbomachine engine of any preceding clause, the high-pressure compressor including eight stages, nine stages, ten stages, or eleven stages.

(206) The turbomachine engine of any preceding clause, the high-pressure turbine including one stage or two stages.

(207) The turbomachine engine of any preceding clause, HSR being given by:

(208) 0HSR = $\frac{1}{k} * N2_{R/L} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$,

where N2.sub.R/L is a redline speed of the high-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM.

(209) The turbomachine engine of any preceding clause, N2.sub.R/L being from 10,580 RPM to 35,788 RPM.

(210) The turbomachine engine of any preceding clause, L.sub.CORE/D.sub.CORE being a function of a high-speed shaft operating parameter HSP.sub.X is given by:

(211) $HSP_X = \frac{(A_{ex})^2 * P_{STD} * OPR_{T/O}}{FN_{T/O} * (N_{Stg} / 10)^2}$,

where N.sub.Stg is the number of stages in the high-pressure compressor, A.sub.EX is an area of the exit stage of the high-pressure compressor, P.sub.AMB is ambient pressure, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to a maximum thrust rating for an engine core configuration, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for the engine core configuration.

(212) The turbomachine engine of any preceding clause, L.sub.CORE/D.sub.CORE being less than MAX(4.8−0.088*(HSP.sub.x), 3.18−0.015*(HSP.sub.x).

(213) The turbomachine engine of any preceding clause, L.sub.CORE/D.sub.CORE being less than 4.08/(HSP.sub.X−8).sup.0.14.

(214) The turbomachine engine of any preceding clause, HSP.sub.X being from 3.8 in.sup.2 to 69.1 in.sup.2.

(215) The turbomachine engine of any preceding clause, A.sub.EX being from 11 in.sup.2 to 95

in.sup.2.
(216) The turbomachine engine of any preceding clause, P.sub.STD being approximately 14.7 psi.
(217) The turbomachine engine of any preceding clause, OPR.sub.T/O being from 26.3 to 82.
(218) The turbomachine engine of any preceding clause, FN.sub.T/O being from 12,674 lbf to 107,480 lbf.
(219) The turbomachine engine of any preceding clause, A.sub.EX being given by A.sub.EX=π*(R.sub.TIP,EX.sup.2−R.sub.HUB,EX.sup.2), where R.sub.TIP,EX is a radius of a tip of a high-pressure compressor blade of the exit stage of the high-pressure compressor, and R.sub.HUB,EX is a radius of a hub of the high-pressure compressor at the exit stage.
(220) The turbomachine engine of any preceding clause, R.sub.TIP,EX being from 4.73 in. to 15.83 in.
(221) The turbomachine engine of any preceding clause, R.sub.HUB,EX being from 4.31 in. to 14.85 in.
(222) The turbomachine engine of any preceding clause, further comprising a power turbine and a low-pressure shaft coupled to the power turbine.
(223) The turbomachine engine of any preceding clause, the high-pressure shaft being characterized by a second high-pressure shaft rating (HSR.sub.LP) given by:
(224) $\mathrm{HSR}_{\mathrm{LP}} = \frac{1}{k} * N1_{r/l} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$,
where N1.sub.r/l is a redline speed of the low-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM.
(225) The turbomachine engine of any preceding clause, HSR.sub.LP being in a range from 0.8 to 1.6.
(226) A turbomachine engine comprises an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and the high-pressure shaft is further characterized by an area ratio high-speed shaft rating (HSP.sub.AR) from 41 to 228.
(227) The turbomachine engine of the preceding clause, a bypass ratio of the turbomachine engine being greater than 8.0. greater than 10.0, or greater than 12.0.
(228) The turbomachine engine of any preceding clause, the high-pressure compressor including eight stages, nine stages, ten stages, or eleven stages.
(229) The turbomachine engine of any preceding clause, the high-pressure turbine including one stage or two stages.
(230) The turbomachine engine of any preceding clause, HSP.sub.AR being a function of a high-speed shaft operating parameter HSP.sub.x, and HSP.sub.x is given by:
(231) $HSP_X = \frac{(A_{ex})^2 * P_{STD} * OPR_{T/O}}{FN_{T/O} * (N_{Stg} / 10)^2}$,
where N.sub.Stg is the number of stages in the high-pressure compressor, A.sub.EX is an area of the exit stage of the high-pressure compressor, P.sub.STD is ambient pressure, OPT.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for an engine core configuration, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for an engine core configuration.
(232) The turbomachine engine of any preceding clause, HSP.sub.AR being less than MAX(280−9*(HSP.sub.x), 82−0.4*(HSP.sub.x)).
(233) The turbomachine engine of any preceding clause, HSP.sub.AR being less than 350/(HSP.sub.x−4).sup.0.5.
(234) The turbomachine engine of any preceding clause, HSP.sub.X being from 3.8 in.sup.2 to 69.1 in.sup.2.

(235) The turbomachine engine of any preceding clause, A.sub.EX being from 11 in.sup.2 to 95 in.sup.2, P.sub.STD is approximately 14.7 psi, OPR.sub.T/O is from 26.3 to 82, and FN.sub.T/O is from 12,674 lbf to 107,480 lbf.
(236) The turbomachine engine of any preceding clause, HSR being given by:
(237) HSR $= \frac{1}{k} * N2_{R/L} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$,
where N2.sub.R/L is a redline speed of the high-pressure shaft, L.sub.CORE is a length of the engine core, D.sub.CORE is a diameter of the engine core, and k is a constant with a value of 10.sup.6 inch-RPM.
(238) The turbomachine engine of any preceding clause, N2.sub.R/L being from 10,580 RPM to 35,788 RPM.
(239) The turbomachine engine of any preceding clause, HSP.sub.AR being given by:
(240) $HSP_{AR} = \frac{\left(\frac{L_{core}}{D_{core}}\right)^2 * AR}{\sqrt{\frac{R_{\mathrm{HUB,IN}}}{R_{\mathrm{TIP,IN}}}} * \sqrt{\frac{R_{\mathrm{TIP,EX}}}{R_{\mathrm{TIP,IN}}}}}$,
where AR is an area ratio of the high-pressure compressor and is the ratio of the area at an inlet of the high-pressure compressor to the area at an exit of the high-pressure compressor (A.sub.IN/A.sub.EX), R.sub.HUB,IN is a radius of a hub at the inlet of the high-pressure compressor, R.sub.TIP,IN is a radius of a tip of a high-pressure compressor blade at the inlet of the high-pressure compressor, and R.sub.TIP,EX is a radius of a tip of a high-pressure compressor blade at an exit stage of the high-pressure compressor.
(241) The turbomachine engine of any preceding clause, a ratio of the of the engine core to the diameter of the engine core (L.sub.CORE/D.sub.CORE) being from 2.1 to 4.3.
(242) The turbomachine engine of any preceding clause, R.sub.HUB,IN/R.sub.TIP,IN being a high-pressure compressor inlet radius ratio, and the high-pressure compressor inlet radius ratio is from 0.4 to 0.6.
(243) The turbomachine engine of any preceding clause, R.sub.TIP,EX/R.sub.TIP,IN being a high-pressure compressor tip radius ratio, and the high-pressure compressor tip radius ratio is from 0.75 to 1.00.
(244) The turbomachine engine of any preceding clause, AR being from 5.6 to 13.9.
(245) The turbomachine engine of any preceding clause, A N being from 85 in.sup.2 to 703 in.sup.2.
(246) The turbomachine engine of any preceding clause, A.sub.EX being from 11 in.sup.2 to 95 in.sup.2.
(247) The turbomachine engine of any preceding clause, further comprising a power turbine and a low-pressure shaft coupled to the power turbine.
(248) The turbomachine engine of any preceding clause, the high-pressure shaft being characterized by a second high-pressure shaft rating (HSR.sub.LP) given by:
(249) $\mathrm{HSR}_{\mathrm{LP}} = \frac{1}{k} * N1_{r/l} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$,
where N1.sub.r/l is a redline speed of the low-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM.
(250) The turbomachine engine of any preceding clause, HSR.sub.LP being in a range from 0.8 to 1.6.
(251) A turbomachine engine comprises an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and the high-pressure shaft being further characterized by an inlet area high-speed shaft rating parameter (HSP_A.sub.IN) from 1,038 in.sup.2 to 5,017 in.sup.2.
(252) The turbomachine engine of the preceding clause, a bypass ratio of the turbomachine engine being greater than 8.0, greater than 10.0, or greater than 12.0.

(253) The turbomachine engine of any preceding clause, the high-pressure compressor including eight stages, nine stages, ten stages, or eleven stages.
(254) The turbomachine engine of any preceding clause, the high-pressure turbine including one stage or two stages.
(255) The turbomachine engine of any preceding clause, HSP_A.sub.IN being a function of a high-speed shaft operating parameter (HSP.sub.X1), and HSP.sub.X1 is given by:
(256) $HSP_{X_1} = \frac{A_{ex} * 1000}{FN_{T/O} * (N_{Stg} / 10)^2}$,
(257) where N.sub.Stg is the number of stages in the high-pressure compressor, A.sub.EX is an area of the exit stage of the high-pressure compressor, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for an engine core configuration.
(258) The turbomachine engine of any preceding clause, HSP_A.sub.IN being less than
(259) $MAX(\frac{4200}{(HSP_{X_1})^{1.5}}, 2850 - 500 * (HSP_{X_1}))$.
(260) The turbomachine engine of any preceding clause, HSP.sub.X1 being from 0.4 to 2.79.
(261) The turbomachine engine of any preceding clause, A.sub.EX being from 11 in.sup.2 to 95 in.sup.2.
(262) The turbomachine engine of any preceding clause, FN.sub.T/O being from 12,674 lbf to 107,480 lbf.
(263) The turbomachine engine of any preceding clause, HSR being given by:
(264) $HSR = \frac{1}{k} * N2_{R/L} * D_{CORE} * (\frac{L_{CORE}}{D_{CORE}})^2$,
where N2.sub.R/L is a redline speed of the high-pressure shaft, L.sub.CORE is a length of the engine core, D.sub.CORE is a diameter of the engine core, and k is a constant with a value of 10.sup.6 inch-RPM.
(265) The turbomachine engine of any preceding clause, N2.sub.R/L being from 10,580 RPM to 35,788 RPM.
(266) The turbomachine engine of any preceding clause, HSP_A.sub.IN being given by:
(267) $0HSP\_A_{IN} = \frac{(\frac{L_{core}}{D_{core}})^2 * A_{IN}}{\sqrt{\frac{R_{HUB,IN}}{R_{TIP\ .Math.\ IN}}} * \sqrt{\frac{R_{TIP,EX}}{R_{TIP,IN}}}}$,
where A.sub.IN is the area at an inlet of the high-pressure compressor, R.sub.HUB,IN is a radius of a hub at the inlet of the high-pressure compressor, R.sub.TIP,IN is a radius of a tip of a high-pressure compressor blade at the inlet of the high-pressure compressor, and R.sub.TIP,EX is a radius of a tip of a high-pressure compressor blade at an exit stage of the high-pressure compressor.
(268) The turbomachine engine of any preceding clause, a ratio of the of the engine core to the diameter of the engine core (L.sub.CORE/D.sub.CORE) being from 2.1 to 4.3.
(269) The turbomachine engine of any preceding clause, A N being from 85 in.sup.2 to 703 in.sup.2.
(270) The turbomachine engine of any preceding clause, R.sub.HUB,IN/R.sub.TIP,IN being a high-pressure compressor inlet radius ratio, and the high-pressure compressor inlet radius ratio is from 0.4 to 0.6.
(271) The turbomachine engine of any preceding clause, R.sub.TIP,EX being from 4.73 in. to 15.83 in.
(272) The turbomachine engine of any preceding clause, R.sub.TIP,IN being from 5.68 in. to 16.32 in.
(273) The turbomachine engine of any preceding clause, further comprising a power turbine and a low-pressure shaft coupled to the power turbine.
(274) The turbomachine engine of any preceding clause, the high-pressure shaft being characterized by a second high-pressure shaft rating (HSR.sub.LP) given by:
(275) $HSR_{LP} = \frac{1}{k} * N1_{r/l} * D_{CORE} * (\frac{L_{CORE}}{D_{CORE}})^2$,

where N1.sub.r/l is a redline speed of the low-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM.
(276) The turbomachine engine of any preceding clause, HSR.sub.LP being in a range from 0.8 to 1.6
(277) The turbomachine engine of any preceding clause, the redline speed of the low-pressure shaft being from 6,345 RPM to 13,225 RPM.
(278) A turbomachine engine comprises an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and the high-pressure shaft being further characterized by an exit rim speed high-speed shaft rating (HSP_U.sub.RIM,R/L) from 0.09 to 1.00 in.sup.−2/3 (ft/s/° R).sup.−3.
(279) The turbomachine engine of the preceding clause, a bypass ratio of the turbomachine engine being greater than 8.0, greater than 10.0, or greater than 12.0.
(280) The turbomachine engine of any preceding clause, the high-pressure compressor including eight stages, nine stages, ten stages, or eleven stages.
(281) The turbomachine engine of any preceding clause, HSP_U.sub.RIM,R/L being a function of a high-speed shaft operating parameter (HSP.sub.X), and HSP.sub.X is given by:
(282) $\mathrm{HSP}_X = \frac{(A_{\mathrm{ex}})^2 * P_{\mathrm{STD}} * \mathrm{OPR}_{T/O}}{\mathrm{FN}_{T/O} * (N_{\mathrm{Stg}} / 10)^2}$,
(283) where N.sub.Stg is the number of stages in the high-pressure compressor, A.sub.EX is an area of the exit stage of the high-pressure compressor, P.sub.STD is standard pressure, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for a engine core configuration, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for an engine core configuration.
(284) The turbomachine engine of any preceding clause, HSP_U.sub.RIM,R/L being less than
(285) $\frac{6.6}{(HSP_X)}$.
(286) The turbomachine engine of any preceding clause, HSP_U.sub.RIM,R/L being less than
(287) $\frac{2.9}{HSP_X^{0.75}}$.
(288) The turbomachine engine of any preceding clause, HSP.sub.X being from 3.8 in.sup.2 to 69.1 in.sup.2.
(289) The turbomachine engine of any preceding clause, A.sub.EX being from 11 in.sup.2 to 95 in.sup.2, P.sub.AMB is approximately 14.7 psi, OPR.sub.T/O is from 26.3 to 82, and FN.sub.T/O is from 12,674 lbf to 107,480 lbf.
(290) The turbomachine engine of any preceding clause, HSR being given by:
(291) $\mathrm{HSR} = \frac{1}{k} * \mathrm{N2}_{R/L} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$,
where N2.sub.R/L is a redline speed of the high-pressure shaft, L.sub.CORE is a length of the engine core, D.sub.CORE is a diameter of the engine core, and k is a constant with a value of 10.sup.6 inch-RPM.
(292) The turbomachine engine of any preceding clause, N2.sub.R/L being from 10,580 RPM to 35,788 RPM.
(293) The turbomachine engine of any preceding clause, HSP_U.sub.RIM,R/L being given by:
(294) $\mathrm{HSP\_U}_{\mathrm{RIM},R/L} = \frac{\left(\frac{L_{CORE}}{D_{CORE}}\right)^2}{N_{stg} * A_{F,\mathrm{IN}}^{1/3}} * \left(\frac{T3_{T/O}}{U_{\mathrm{RIM},R/L}}\right)^3$,
(295) where N.sub.stg is a number of stages of the high-pressure compressor, T3.sub.T/O is a temperature at the exit of the high-pressure compressor at takeoff flight conditions, A.sub.F,IN is a frontal area of the high-pressure compressor, and U.sub.RIM,R/L is an exit rim speed of the high-

pressure compressor at redline speeds of the high-pressure shaft.
(296) The turbomachine engine of any preceding clause, a ratio of the length of the engine core to the diameter of the engine core (L.sub.CORE/D.sub.CORE) being from 2.1 to 4.3.
(297) The turbomachine engine of any preceding clause, N stg being eight stages, nine stage, ten stage, or eleven stages.
(298) The turbomachine engine of any preceding clause, A.sub.F,IN being from 101 to 837.
(299) The turbomachine engine of any preceding clause, U.sub.RIM,R/L being given by:
(300) $U_{\mathrm{RIM},R/L} = \frac{*N2_{R/L}}{30} * \frac{R_{\mathrm{HUB},EX}}{12}$,
where R.sub.HUB,EX is a radius of a hub at an exit stage of the high-pressure compressor.
(301) The turbomachine engine of any preceding clause, T3.sub.T/O being given by:
(302) $T3_{T/O} = T25_{T/O} * (3.465 * \mathrm{AR} - 5.7)^{\frac{-1}{*\ \mathrm{Poly}}}$,
where T25.sub.T/O is a temperature at an inlet of the high-pressure compressor, AR is an area ratio of the high-pressure compressor and is the ratio of the area at the inlet of the high-pressure compressor to the area at an exit of the high-pressure compressor (A.sub.IN/A.sub.EX), γ is a gas constant of air and is equal to 1.37, and η.sub.Poly is a compressor efficiency of the high-pressure compressor and is approximately equal to 0.9.
(303) The turbomachine engine of any preceding clause, AR being from 5.6 to 13.9.
(304) The turbomachine engine of any preceding clause, T25.sub.T/O being from 579° R to 803° R.
(305) The turbomachine engine of any preceding clause, T25.sub.T/O being given by:
(306) $T25_{T/O} = T_{\mathrm{ISA}} * \left(\frac{1.25 * \mathrm{OPR}_{T/O}}{3.465 * \mathrm{AR} - 5.7}\right)^{\frac{-1}{*\ \mathrm{Poly}}} + T_{\mathrm{IC}}$,
where T.sub.ISA is ambient temperature and is approximately equal to 545.67° R, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for a engine core configuration, γ is a gas constant of air and is equal to 1.37, η.sub.Poly is an overall compression efficiency of the turbomachine engine and is approximately equal to 0.9, and T.sub.IC is an intercooler temperature upstream of the high-pressure compressor.
(307) The turbomachine engine of any preceding clause, further comprising a power turbine and a low-pressure shaft coupled to the power turbine.
(308) The turbomachine engine of any preceding clause, the high-pressure shaft being characterized by a second high-pressure shaft rating (HSR.sub.LP) given by:
(309) $0\mathrm{HSR}_{\mathrm{LP}} = \frac{1}{k} * N1_{r/l} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$,
where N1.sub.r/l is a redline speed of the low-pressure shaft, k is a constant with a value of 10.sup.6 inch-RPM, and HSR.sub.LP is in a range from 0.8 to 1.6.
(310) A turbomachine engine comprises an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and the high-pressure shaft being further characterized by a radius ratio high-speed shaft rating (HSP.sub.RR) from 9.1 to 62.5.
(311) The turbomachine engine of the preceding clause, a bypass ratio of the turbomachine engine being greater than 8.0, greater than 10.0, or greater than 12.0.
(312) The turbomachine engine of any preceding clause, the high-pressure compressor including eight stages, nine stages, ten stages, or eleven stages.
(313) The turbomachine engine of any preceding clause, the high-pressure turbine including one stage or two stages.
(314) The turbomachine engine of any preceding clause, HSP.sub.RR being a function of a high-speed shaft operating parameter (HSP.sub.X), and HSP.sub.X is given by:

(315) $\mathrm{HSP}_X = \frac{(A_{\mathrm{ex}})^2 * P_{\mathrm{STD}} * \mathrm{OPR}_{T/O}}{\mathrm{FN}_{T/O} * (N_{\mathrm{Stg}} / 10)^2}$,
where N.sub.Stg is the number of stages in HP compressor, A.sub.EX is an area of the exit stage of the high-pressure compressor, P.sub.STD is standard pressure, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for an engine core configuration, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for an engine core configuration.
(316) The turbomachine engine of any preceding clause, HSP.sub.RR being less than MAX(77−2.6*(HSP.sub.x), 27−0.2*(HSP.sub.x)).
(317) The turbomachine engine of any preceding clause, HSP.sub.RR being less than
(318) $\frac{165}{HSP_X^{0.6}}$.
(319) The turbomachine engine of any preceding clause, HSP.sub.X being from 3.8 in.sup.2 to 69.1 in.sup.2.
(320) The turbomachine engine of any preceding clause, A.sub.EX being from 11 in.sup.2 to 95 in.sup.2, P.sub.AMB is approximately 14.7 psi, OPR.sub.T/O is from 26.3 to 82, and FN.sub.T/O is from 12,674 lbf to 107,480 lbf.
(321) The turbomachine engine of any preceding clause, HSR being given by:
(322) $\mathrm{HSR} = \frac{1}{k} * N2_{R/L} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$,
where N2.sub.R/L is a redline speed of the high-pressure shaft, L.sub.CORE is a length of the engine core, D.sub.CORE is a diameter of the engine core, and k is a constant with a value of 10.sup.6 inch-RPM.
(323) The turbomachine engine of any preceding clause, N2.sub.R/L being from 10,580 RPM to 35,788 RPM.
(324) The turbomachine engine of any preceding clause, HSP.sub.RR being given by:
(325) $\mathrm{HSP}_{\mathrm{RR}} = \frac{\left(\frac{L_{\mathrm{core}}}{D_{\mathrm{core}}} * \frac{T_{25_{T/O}}}{T_{\mathrm{STD}}}\right)^2}{\sqrt{\frac{R_{\mathrm{HUB,IN}}}{R_{\mathrm{TIP,IN}}}} * \sqrt{\frac{R_{\mathrm{TIP,EX}}}{R_{\mathrm{TIP,IN}}}}}$
where T25.sub.T/O is a temperature at an inlet of the high-pressure compressor, T.sub.STD is standard day temperature and is equal to 518.67° R, R.sub.HUB,IN is a radius of a hub at the inlet of the high-pressure compressor, R.sub.TIP,IN is a radius of a tip of a high-pressure compressor blade at the inlet of the high-pressure compressor, and R.sub.TIP,EX is a radius of a tip of a high-pressure compressor blade at an exit stage of the high-pressure compressor.
(326) The turbomachine engine of any preceding clause, a ratio of the of the engine core to the diameter of the engine core (L.sub.CORE/D.sub.CORE) being from 2.1 to 4.3.
(327) The turbomachine engine of any preceding clause, R.sub.HUB,IN/R.sub.TIP,IN being a high-pressure compressor inlet radius ratio, and the high-pressure compressor inlet radius ratio is from 0.4 to 0.6.
(328) The turbomachine engine of any preceding clause, R.sub.TIP,EX/R.sub.TIP,IN being a high-pressure compressor tip radius ratio, and the high-pressure compressor tip radius ratio is from 0.75 to 1.0.
(329) The turbomachine engine of any preceding clause, T25.sub.T/O being from 579° R to 803° R.
(330) The turbomachine engine of any preceding clause, T25.sub.T/O being given by:
(331) $T25_{T/O} = T_{\mathrm{ISA}} * \left(\frac{1.25 * \mathrm{OPR}_{T/O}}{3.465 * \mathrm{AR} - 5.7}\right)^{\frac{-1}{*\ \mathrm{Poly}}} + T_{\mathrm{IC}}$,
where T.sub.ISA is ambient temperature and is approximately equal to 545.67° R, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to a maximum thrust rating for an engine core configuration, γ is a gas constant of air and is equal to 1.37, η.sub.Poly is an overall compression efficiency of the turbomachine engine and is approximately equal to 0.9, and T.sub.IC is an intercooler temperature upstream of the HP

compressor.
(332) The turbomachine engine of any preceding clause, OPR.sub.T/O being from 26.3 to 82.
(333) The turbomachine engine of any preceding clause, T.sub.IC being from −100° R to 0° R.
(334) The turbomachine engine of any preceding clause, AR being from 5.6 to 13.9.
(335) The turbomachine engine of any preceding clause, wherein the high-pressure shaft first mode margin with respect to the low-pressure shaft redline speed is given by:
(336) $-0.1 > \left(\frac{0.55}{(HSR_{LP})^2} + LST\right) > 0$,
wherein LST accounts for the effects that the HPC pressure ratio and the HPC exit temperature can have on the first mode.
(337) The turbomachine engine of any preceding clause, wherein the high-pressure shaft first mode margin with respect to the low-pressure shaft redline speed is given by:
(338) $-0.2 > \left(\frac{0.55}{(HSR_{LP})^2} + LST\right) > 0$,
wherein LST accounts for the effects that the HPC pressure ratio and the HPC exit temperature can have on the first mode.
(339) The turbomachine engine of any preceding clause, wherein the high-pressure shaft first mode margin with respect to the low-pressure shaft redline speed is given by:
(340) $-0.3 > \left(\frac{0.55}{(HSR_{LP})^2} + LST\right) > 0$,
wherein LST accounts for the effects that the HPC pressure ratio and the HPC exit temperature can have on the first mode.
(341) The turbomachine engine of any preceding clause, wherein the high-pressure shaft first mode margin with respect to the low-pressure shaft redline speed is given by:
(342) $\left(\frac{0.55}{(HSR_{LP})^2} + LST\right) > -0.1$,
wherein LST accounts for the effects that the HPC pressure ratio and the HPC exit temperature can have on the first mode.
(343) The turbomachine engine of any preceding clause, wherein LST is from −0.15 to −0.67.
(344) The turbomachine engine of any preceding clause, wherein the high-pressure shaft second mode margin with respect to the high-pressure shaft redline speed is given by:
(345) $0(-0.1215 * HSR + (\frac{2 * HST - 1}{3})) < -0.1$,
wherein HST accounts for the effects that the HPC pressure ratio and the HPC exit temperature have on the third mode.
(346) The turbomachine engine of any preceding clause, wherein the high-pressure shaft third mode margin with respect to the high-pressure shaft redline speed is given by: −0.1>(−0.1822*HSR+HST)>0, wherein HST accounts for the effects that the HPC pressure ratio and the HPC exit temperature have on the third mode.
(347) The turbomachine engine of any preceding clause, wherein the high-pressure shaft third mode margin with respect to the high-pressure shaft redline speed is given by: −0.2>(−0.1822*HSR+HST)>0, wherein HST accounts for the effects that the HPC pressure ratio and the HPC exit temperature have on the third mode.
(348) The turbomachine engine of any preceding clause, wherein the high-pressure shaft third mode margin with respect to the high-pressure shaft redline speed is given by: −0.3>(−0.1822*HSR+HST)>0, wherein HST accounts for the effects that the HPC pressure ratio and the HPC exit temperature have on the third mode.
(349) The turbomachine engine of any preceding clause, wherein the high-pressure shaft third mode margin with respect to the high-pressure shaft redline speed is given by: (−0.1822*HSR+HST)>−0.1, wherein HST accounts for the effects that the HPC pressure ratio and the HPC exit temperature have on the third mode.
(350) The turbomachine engine of any preceding clause, wherein HST is from 0.46 to 0.78.
(351) The turbomachine engine of any preceding clause, wherein HST is given by:

HST=−0.726*T25/T.sub.STD+1.61, wherein T25 is from 615° R to 855° R and T.sub.STD is the standard temperature defined by a constant value of 518.67° R
(352) The turbomachine engine of any preceding clause, further comprising a power turbine and a low-pressure shaft coupled to the power turbine, the high-pressure shaft being characterized by a second high-pressure shaft rating (HSR.sub.LP) given by:
(353) $HSR_{LP} = \frac{1}{k} * N1_{r/1} * D_{CORE^*} (\frac{L_{CORE}}{D_{CORE}})^2$,
where N1.sub.r/l is a redline speed of the low-pressure shaft, k is a constant with a value of 10.sup.6 inch-RPM, and HSR.sub.LP is in a range from 0.8 to 1.6.
(354) The turbomachine engine of any preceding clause, further comprising an intermediate-pressure turbine, an intermediate-pressure compressor, and an intermediate-pressure shaft coupled to the intermediate-pressure turbine and the intermediate-pressure compressor.
(355) The turbomachine engine of any preceding clause, further comprising an intercooler between the high-pressure compressor and the low-pressure compressor.
(356) The turbomachine engine of any preceding clause, further comprising a fan, the fan being directly coupled to the low-pressure shaft.
(357) The turbomachine engine of any preceding clause, further comprising a fan and a gearbox assembly, the fan coupled to the low-pressure shaft through the gearbox assembly.
(358) The turbomachine engine of any preceding clause, the turbomachine engine being a ducted turbine engine.
(359) The turbomachine engine of any preceding clause, the turbomachine engine being an unducted turbine engine.
(360) The turbomachine engine of any preceding clause, the turbomachine engine being a three stream turbine engine.
(361) The turbomachine engine of any preceding clause, the fan including a plurality of fan blades, the plurality of fan blades being configured to pitch about a pitch axis.
(362) The turbomachine engine of any preceding clause, the turbomachine engine including a counter rotating low-pressure architecture in which two shafts of the turbomachine engine rotate in opposite directions and pass through the engine core.
(363) The turbomachine engine of any preceding clause, the turbomachine engine including a vaneless counter rotating turbine.
(364) The turbomachine engine of any preceding clause, L.sub.CORE being from 36 in. to 67 in.
(365) The turbomachine engine of any preceding clause, at least one of the high-pressure compressor, the high-pressure turbine, or the power turbine including a ceramic matrix composite (CMC) material.
(366) The turbomachine engine of the preceding clause, the power turbine including the CMC material.
(367) The turbomachine engine of the preceding clause, the CMC material being a first CMC material, and the high-pressure turbine including the first CMC material or a second CMC material.
(368) The turbomachine engine of the preceding clause, the high-pressure compressor including the first CMC material or the second CMC material or a third CMC material.
(369) The turbomachine engine of any preceding clause, the high-pressure turbine including the CMC material.
(370) The turbomachine engine of the preceding clause, the high-pressure turbine including at least one nozzle and at least one airfoil, the at least one nozzle, the at least one airfoil, or both the at least one nozzle and the at least one airfoil including the CMC material.
(371) The turbomachine engine of any preceding clause, the high-pressure turbine having one stage or two stages, and at least one stage including the CMC material.
(372) The turbomachine engine of any preceding clause, the CMC material being a first CMC material, and the power turbine including the first CMC material or a second CMC material.

(373) The turbomachine engine of any preceding clause, the high-pressure compressor including the first CMC material or the second CMC material or a third CMC material.
(374) The turbomachine engine of any preceding clause, the high-pressure compressor including the CMC material.
(375) The turbomachine engine of any preceding clause, the high-pressure compressor having eight stages, nine stages, ten stages, or eleven stages, and at least one stage including the CMC material.
(376) The turbomachine engine of any preceding clause, the high-pressure compressor having nine stages and at least one stage of the nine stages includes the CMC material.
(377) The turbomachine engine of any preceding clause, the CMC material being a first CMC material, and the high-pressure turbine including the first CMC material or a second CMC material.
(378) The turbomachine engine of any preceding clause, the power turbine including the first CMC material, the second CMC material, or a third CMC material.
(379) The turbomachine engine of any preceding clause, the first CMC material and the second CMC material being the same materials.
(380) The turbomachine engine of any preceding clause, the first CMC material and the second CMC material being different materials.
(381) The turbomachine engine of any preceding clause, the third CMC material being the same material as the first CMC material, the second CMC material, or both the first CMC material and the second CMC material.
(382) The turbomachine engine of any preceding clause, the third CMC material being a different material than the first CMC material, the second CMC material, or both the first CMC material and the second CMC material.
(383) A method of operating the turbomachine engine of any preceding clause, the method comprising operating the turbomachine engine to generate an engine thrust, a redline speed of the high-pressure shaft being from 10,580 RPM to 35,788 RPM.
(384) Although the foregoing description is directed to the preferred embodiments of the present disclosure, other variations and modifications will be apparent to those skilled in the art and may be made without departing from the spirit or the scope of the disclosure. Moreover, features described in connection with one embodiment of the present disclosure may be used in conjunction with other embodiments, even if not explicitly stated above.

Claims

1. A turbomachine engine comprising: an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, the engine core including a core forward bearing and a core aft bearing, the core forward bearing being positioned forward of a stage of the high-pressure compressor and the core aft bearing being positioned aft of a stage of the high-pressure turbine, the engine core having a length (L.sub.CORE) defined from the core forward bearing to the core aft bearing, and the high-pressure compressor having an exit stage diameter (D.sub.CORE); and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and a ratio of L.sub.CORE/D.sub.CORE is greater than or equal to 2.1 and less than $\frac{4.08}{(\mathrm{HSP}_X - 8)^{0.14}}$ wherein HSR is given by: $\mathrm{HSR} = \frac{1}{k} * N2_{R/L} * D_{\mathrm{CORE}} * \left(\frac{L_{\mathrm{CORE}}}{D_{\mathrm{CORE}}}\right)^2$, where N2.sub.R/L is a redline speed of the high-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM, and wherein HSP.sub.X is given by: $\mathrm{HSP}_X = \frac{(A_{\mathrm{ex}})^2 * P_{\mathrm{STD}} * \mathrm{OPR}_{\frac{T}{O}}}{\mathrm{FN}_{\frac{T}{O}} * \left(\frac{N_{\mathrm{Stg}}}{10}\right)^2}$, where N.sub.Stg is a number of stages in the high-pressure compressor, A.sub.EX is an area of an exit stage of the high-pressure compressor, P.sub.STD is standard pressure, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff

flight conditions corresponding to a maximum thrust rating for an engine core configuration, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for the engine core configuration.
2. The turbomachine engine of claim 1, wherein a number of stages in the high-pressure compressor is one of eight stages, nine stages, ten stages, or eleven stages.
3. The turbomachine engine of claim 1, wherein the high-pressure turbine includes one stage or two stages.
4. The turbomachine engine of claim 1, wherein an exhaust gas temperature of the turbomachine engine at redline speeds of the high-pressure shaft is from 1,063° C. to 1,282° C.
5. The turbomachine engine of claim 1, wherein HSP.sub.X is from 3.8 in.sup.2 to 69.1 in.sup.2.
6. The turbomachine engine of claim 1, wherein A.sub.EX is from 11 in.sup.2 to 95 in.sup.2.
7. The turbomachine engine of claim 1, wherein P.sub.STD is approximately 14.7 psi.
8. The turbomachine engine of claim 1, wherein OPR.sub.T/O is from 26.3 to 82.
9. The turbomachine engine of claim 1, wherein FN.sub.T/O is from 12,674 lbf to 107,480 lbf.
10. The turbomachine engine of claim 1, wherein A.sub.EX is given by A.sub.EX=π*(R.sub.TIP,EX.sup.2−R.sub.HUB,EX.sup.2), where R.sub.TIP,EX is a radius of a tip of a high-pressure compressor blade of the exit stage of the high-pressure compressor, and R.sub.HUB,EX is a radius of a hub of the high-pressure compressor at the exit stage.
11. The turbomachine engine of claim 10, wherein R.sub.TIP,EX is from 4.73 in. to 15.83 in.
12. The turbomachine engine of claim 10, wherein R.sub.HUB,EX is from 4.31 in. to 14.85 in.
13. A method of operating the turbomachine engine of claim 1, the method comprising operating the turbomachine engine to generate an engine thrust, a redline speed of the high-pressure shaft being from 10,580 RPM to 35,788 RPM.
14. The turbomachine engine of claim 1, wherein the stage of the high-pressure compressor is a first stage and the stage of the high-pressure turbine is a last stage such that the core forward bearing is positioned forward of the first stage of the high-pressure compressor and the core aft bearing is positioned aft of the last stage of the high-pressure turbine.
15. A turbomachine engine comprising: an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, the engine core including a core forward bearing and a core aft bearing, the core forward bearing being positioned forward of a stage of the high-pressure compressor and the core aft bearing being positioned aft of a stage of the high-pressure turbine, the engine core having a length (L.sub.CORE) defined from the core forward bearing to the core aft bearing, and the high-pressure compressor having an exit stage diameter (D.sub.CORE); a power turbine in flow communication with the high-pressure turbine; a low-pressure shaft coupled to the power turbine; and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and a ratio of L.sub.CORE/D.sub.CORE is greater than or equal to 2.1 and less than $\frac{4.08}{(HSP_X - 8)^{0.14}}$ wherein HSR is given by: $HSR = \frac{1}{k} * N2_{R/L} * D_{CORE} * \left(\frac{L_{CORE}}{D_{CORE}}\right)^2$, where N2.sub.R/L is a redline speed of the high-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM, and wherein HSP.sub.X is given by: $HSP_X = \frac{(A_{ex})^2 * P_{STD} * OPR_{T/O}}{FN_{T/O} * \left(\frac{N_{Stg}}{10}\right)^2}$, where N.sub.Stg is a number of stages in the high-pressure compressor, A.sub.EX is an area of an exit stage of the high-pressure compressor, P.sub.STD is standard pressure, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to a maximum thrust rating for an engine core configuration, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for the engine core configuration.
16. The turbomachine engine of claim 15, wherein the high-pressure shaft is characterized by a

second high-pressure shaft rating (HSR.sub.LP) from 0.8 to 1.6, and HSR.sub.LP is given by: $HSR_{LP} = \frac{1}{k} * N1_{r/1} * D_{CORE} * (\frac{L_{CORE}}{D_{CORE}})^2$, where N1.sub.r/l is a redline speed of the low-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM.
17. The turbomachine engine of claim 15, wherein N2.sub.R/L is from 10,580 RPM to 35,788 RPM.
18. The turbomachine engine of claim 15, wherein HSP.sub.X is from 3.8 in.sup.2 to 69.1 in.sup.2.
19. The turbomachine engine of claim 15, wherein a number of stages in the high-pressure compressor is one of eight stages, nine stages, ten stages, or eleven stages.
20. The turbomachine engine of claim 15, wherein A.sub.EX is from 11 in.sup.2 to 95 in.sup.2.
21. The turbomachine engine of claim 15, wherein P.sub.STD is approximately 14.7 psi.
22. The turbomachine engine of claim 15, wherein OPR.sub.T/O is from 26.3 to 82.
23. The turbomachine engine of claim 15, wherein FN.sub.T/O is from 12,674 lbf to 107,480 Ibf.
24. A turbomachine engine comprising: an engine core including a high-pressure compressor, a high-pressure turbine, and a combustion chamber in flow communication with the high-pressure compressor and the high-pressure turbine, the engine core including a core forward bearing and a core aft bearing, the core forward bearing being positioned forward of a stage of the high-pressure compressor and the core aft bearing being positioned aft of a stage of the high-pressure turbine, the engine core having a length (L.sub.CORE) defined from the core forward bearing to the core aft bearing, and the high-pressure compressor having an exit stage diameter (D.sub.CORE), wherein a number of stages in the high-pressure compressor is one of eight stages, nine stages, ten stages, or eleven stages, and the high-pressure turbine includes one stage or two stages; and a high-pressure shaft coupled to the high-pressure compressor and the high-pressure turbine, the high-pressure shaft characterized by a high-speed shaft rating (HSR) from 1.5 to 6.2, and a ratio of L.sub.CORE/D.sub.CORE is greater than or equal to 2.1 and less than $\frac{4.08}{(HSP_X - 8)^{0.14}}$ wherein HSR is given by: $HSR = \frac{1}{k} * N2_{R/L} * D_{CORE} * (\frac{L_{CORE}}{D_{CORE}})^2$, where N2.sub.R/L is a redline speed of the high-pressure shaft, and k is a constant with a value of 10.sup.6 inch-RPM, wherein HSP.sub.X is given by: $HSP_X = \frac{(A_{ex})^2 * P_{STD} * OPR_{\frac{T}{O}}}{FN_{\frac{T}{O}} * (\frac{N_{Stg}}{10})^2}$, where N.sub.Stg is the number of stages in the high-pressure compressor, A.sub.EX is an area of an exit stage of the high-pressure compressor, P.sub.STD is standard pressure, OPR.sub.T/O is an overall pressure ratio of the turbomachine engine at takeoff flight conditions corresponding to a maximum thrust rating for an engine core configuration, and FN.sub.T/O is a sea-level static thrust of the turbomachine engine at takeoff flight conditions corresponding to the maximum thrust rating for the engine core configuration.
25. The turbomachine engine of claim 24, wherein N2.sub.R/L is from 10,580 RPM to 35,788 RPM.
26. The turbomachine engine of claim 24, wherein HSP.sub.X is from 3.8 in.sup.2 to 69.1 in.sup.2.
27. The turbomachine engine of claim 24, wherein A.sub.EX is from 11 in.sup.2 to 95 in.sup.2.
28. The turbomachine engine of claim 24, wherein P.sub.STD is approximately 14.7 psi.
29. The turbomachine engine of claim 24, wherein OPR.sub.T/O is from 26.3 to 82.
30. The turbomachine engine of claim 24, wherein FN.sub.T/O is from 12,674 lbf to 107,480 lbf.