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System and method for measuring an axial position of a rotating component

Abstract

Systems and methods for measuring an axial position of a phonic wheel or other rotating component are provided. The system includes a phonic wheel rotatable about a rotation axis and translatable along the rotation axis, a first sensor, a second sensor and a computer. The phonic wheel includes an inclined tooth having an axially non-uniform radial height and a reference tooth having an axially uniform radial height. The first sensor generates a positioning signal indicative of a gap between the inclined tooth and the first sensor. The second sensor generates a reference signal indicative of a gap between the reference tooth and the reference sensor. The first and second sensors have different orientations. The computer generates an output indicative of the axial position of the phonic wheel based on the positioning signal and the reference signal.

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Background/Summary

TECHNICAL FIELD

(1) The disclosure relates generally to measuring an axial position of a rotating component such as a phonic wheel of a feedback system for pitch-adjustable blades of bladed rotors of aircraft.

BACKGROUND

(2) On aircraft propeller systems that have pitch-adjustable (i.e., variable pitch) propeller blades, it

is desirable to provide accurate feedback on the angular position, sometimes referred to as “beta angle”, of the propeller blades. Such feedback can be used to control the angular position in a feedback control loop based on a requested set point. The angular position feedback can also be used to ensure that the propeller is not inadvertently commanded to transition into excessively low or reverse beta angles. Due to the limited space available on aircraft engines, providing systems that can accurately and reliably provide positional feedback of the propeller blades is challenging.

SUMMARY

(3) In one aspect, the disclosure describes a system for measuring an axial position of a phonic wheel. The system comprises: the phonic wheel rotatable about a rotation axis and translatable along the rotation axis, the phonic wheel including: a body; an inclined tooth attached to the body and extending axially, a top surface of the inclined tooth being inclined relative to the rotation axis; and a reference tooth attached to the body and extending axially, a top surface of the reference tooth being parallel to the rotation axis; an inclined sensor adjacent the phonic wheel and configured to generate a positioning signal indicative of a gap between the top surface of the inclined tooth and the inclined sensor along a sensor axis of the inclined sensor as the phonic wheel is rotated relative to the inclined sensor, the sensor axis of the inclined sensor being non-perpendicular to the rotation axis; a reference sensor adjacent the phonic wheel and configured to generate a reference signal indicative of a gap between the top surface of the reference tooth and the reference sensor along a sensor axis of the reference sensor as the phonic wheel is rotated relative to the reference sensor, the sensor axis of the reference sensor being perpendicular to the rotation axis; and a computer operatively connected to the inclined sensor and to the reference sensor, the computer being configured to generate an output indicative of the axial position of the phonic wheel based on the positioning signal and the reference signal.

(4) In another aspect, the disclosure describes an aircraft engine comprising: a bladed rotor rotatable about a rotation axis and having pitch-adjustable blades; a toothed ring coaxial with the rotation axis, the toothed ring including: an inclined tooth extending axially relative to the rotation axis and having an axially non-uniform radial height; and a reference tooth extending axially relative to the rotation axis and having an axially uniform radial height; an inclined sensor adjacent to the toothed ring, the inclined sensor or the toothed ring being rotatable about the rotation axis and translatable axially along the rotation axis as a function of a pitch angle of the pitch-adjustable blades, the inclined sensor being configured to generate a positioning signal indicative of a gap between the inclined tooth and the inclined sensor along a sensor axis of the inclined sensor as relative rotation between the toothed ring and the inclined sensor occurs, the sensor axis of the inclined sensor being perpendicular to a top surface of the inclined tooth; a reference sensor fixedly mounted relative to the inclined sensor and adjacent to the toothed ring, the reference sensor being configured to generate a reference signal indicative of a gap between the reference tooth and the reference sensor along a sensor axis of the reference sensor as relative rotation between the toothed ring and the reference sensor occurs, the sensor axis of the reference sensor being perpendicular to the rotation axis; and a computer operatively connected to the inclined sensor and to the reference sensor, the computer being configured to generate an output indicative of a relative axial position between the toothed ring and the inclined sensor based on the positioning signal and the reference signal.

(5) In a further aspect, the disclosure describes a method for measuring an axial position of a phonic wheel. The method comprises: directing a first magnetic field from a first sensor toward a location that a first tooth of the phonic wheel is expected to occupy as the phonic wheel rotates about a rotation axis relative to the first sensor, the first tooth extending axially relative to the rotation axis and having an axially non-uniform radial height, the first sensor being inclined relative to an orientation perpendicular to the rotation axis; detecting a variation in the first magnetic field caused by movement of the first tooth in the first magnetic field; generating a first feedback signal based on the detection of the variation in the first magnetic field; directing a second

magnetic field from a second sensor toward a location that a second tooth of the phonic wheel is expected to occupy as the phonic wheel rotates relative to the second sensor about the rotation axis, the second tooth extending axially relative to the rotation axis and having an axially uniform radial height; detecting a variation in the second magnetic field caused by movement of the second tooth in the second magnetic field; generating a second feedback signal based on the detection of the variation in the second magnetic field; and generating an output indicative of the axial position of the phonic wheel based on the first feedback signal and the second signal.
(6) Further details of these and other aspects of the subject matter of this application will be apparent from the detailed description included below and the drawings.

Description

DESCRIPTION OF THE DRAWINGS
(1) Reference is now made to the accompanying drawings, in which:
(2) FIG. **1** is an axial cross-section view of an aircraft engine coupled to a bladed rotor with pitch-adjustable blades and including a system for measuring an axial position of a rotating component as described herein;
(3) FIGS. **2**, **2**A and **2**B show a schematic representation of an exemplary system including a phonic wheel for measuring an axial position of a rotating component;
(4) FIG. **3** is a partial schematic representation of another exemplary phonic wheel that may be part of the system of FIG. **2**;
(5) FIG. **4**A is a partial schematic cross-section view of the phonic wheel of FIG. **3** taken along line **4**A-**4**A in FIG. **3**;
(6) FIG. **4**B is a partial schematic cross-section view of the phonic wheel of FIG. **3** taken along line **4**B-**4**B in FIG. **3**;
(7) FIG. **5** is a schematic representation of an exemplary computer of the system of FIG. **2**;
(8) FIG. **6** is a flow diagram of an exemplary method for measuring an axial position of a phonic wheel;
(9) FIG. **7** is another flow diagram of the method for measuring the axial position of the phonic wheel;
(10) FIG. **8** is a graph illustrating an exemplary relationship between an amplitude of a sensor signal and an air gap between the sensor and a top of a tooth of the phonic wheel; and
(11) FIG. **9** is a table defining a relationship between the air gap, an axial position of the phonic wheel and a pitch angle of a bladed rotor.
DETAILED DESCRIPTION
(12) The following description relates to phonic wheels and related systems and methods useful for measuring an axial position of a phonic wheel or of a component connected to the phonic wheel. In some embodiments, the phonic wheel may have an inclined tooth having an axially non-uniform radial height and one or more reference teeth having axially uniform radial heights. The presence of the inclined tooth may be sensed using a first sensor and the presence of the reference tooth (or teeth) may be sensed using a second sensor. The first sensor and the second sensor may have different orientations tailored for the inclined tooth and for the reference tooth (or teeth) respectively. In some embodiments, the use of the one or more reference teeth may reduce the need for calibration of the system. In some embodiments, the use of differently-orientated sensors for detecting the inclined tooth and the reference tooth (or teeth) respectively may improve compatibility between signals obtained from the different sensors and may improve accuracy in measuring the axial position of the phonic wheel or other rotating component.
(13) The phonic wheels, systems and methods described herein may be useful in providing feedback on the angular position (i.e., pitch angle) of pitch-adjustable blades on aircraft bladed

rotors such as aircraft propellers for example. However, the phonic wheels, systems and methods disclosed herein may also be used in other applications.
(14) The terms “perpendicular” and “parallel” as used herein may permissibly include variations from purely perpendicular and parallel such as variations associated with dimensional tolerances of components and assemblies.
(15) The term “substantially” as used herein may be applied to modify any quantitative representation which could permissibly vary without resulting in a change in the basic function to which it is related.
(16) The terms “connected” and “attached” may include both direct connection and attachment (in which two elements contact each other) and indirect connection and attachment (in which at least one additional element is located between the two elements).
(17) Aspects of various embodiments are described through reference to the drawings.
(18) FIG. **1** is an axial cross-section view of an exemplary aircraft engine **10** coupled to bladed rotor **12** (e.g., propeller) for an aircraft. Engine **10** may be a gas turbine engine of a type typically provided for use in subsonic flight, including inlet **14**, into which ambient air is received, (e.g., multi-stage) compressor **16** for pressurizing the air, combustor **18** in which the compressed air is mixed with fuel and ignited for generating an annular stream of hot combustion gases, and turbine section **20** for extracting energy from the combustion gases. Turbine section **20** may include high-pressure turbine **22**, which may drive compressor **16** and other accessories, and power turbine **24** which may rotate separately from high-pressure turbine **22** and which may drive power shaft **26**, which may be drivingly coupled to bladed rotor **12** via reduction gearbox **28**. Combustion gases may be evacuated through exhaust duct **30** after passing through turbine section **20**.
(19) Bladed rotor **12** may include a plurality of pitch-adjustable blades **32** extending radially from hub **34** and being circumferentially distributed relative to hub **34** of bladed rotor **12**. Each pitch-adjustable blade **32** may be angularly adjustable about a respective axis B. Accordingly, each blade **32** may be rotatable about axis B using any suitable mechanism so that the pitch of blades **32** may be adjusted collectively in unison for different phases of operation (e.g., feather, forward thrust and reverse thrust) of engine **10** and/or of an aircraft to which engine **10** and bladed rotor **12** may be mounted. Even though FIG. **1** illustrates bladed rotor **12** as a propeller suitable for fixed-wing aircraft, it is understood that aspects of this disclosure are also applicable to other types of bladed rotors such as a main rotor of a rotary-wing aircraft (e.g., helicopter) for example.
(20) Bladed rotor **12** may be mounted for rotation about rotation axis RA. In some embodiments, rotation axis RA may, but not necessarily, be coaxial with an axis of rotation of power shaft **26**. FIG. **1** also schematically shows system **36** for measuring an axial position of a rotating component (e.g., phonic wheel **38** shown in FIG. **2**) which may be associated with bladed rotor **12**. As explained further below the axial position of the rotating component may be indicative of the pitch angle (sometimes called beta angle) of pitch-adjustable blades **32** and may be used as a feedback signal for controlling the pitch angle of blades **32**.
(21) FIG. **2** is a schematic representation of system **36** for measuring an axial position of a rotating component viewed along rotation axis RA. In some embodiments, system **36** may provide feedback indicative of pitch angle **52** of pitch-adjustable blades **32** of bladed rotor **12**. System **36** may be configured to interface with known or other adjustable blade systems to permit the detection of pitch angle **52** of blades **32**. In some embodiments, system **36** may include phonic wheel **38** (or phonic wheel **138** of FIG. **3**), sensors **40**A, **40**B and a detection unit such as computer **42** for example.
(22) In some embodiments, phonic wheel **38** may be connected for common rotation (e.g., torque transmission) and axial translation with another component such as shaft **44**. Phonic wheel **38** and shaft **44** (both of which being partially shown in FIG. **2**) may be rotatable about rotation axis RA in the direction of arrow R and may also be axially translatable along rotation axis RA. Sensors **40**A, **40**B may be mounted to fixed structure **41** and be adjacent to phonic wheel **38**. In other words,

sensors **40**A, **40**B may be fixed relative to rotating and translating phonic wheel **38**.
(23) Alternatively, phonic wheel **38** could instead be used as a fixed toothed ring that is not rotatable about rotation axis RA. For example, in some embodiments, sensors **40**A, **40**B may be mounted to shaft **44** for rotation about rotation axis RA in the direction of arrow R and also be axially translatable along rotation axis RA. In other words, sensors **40**A, **40**B may be rotatable and translatable relative to stationary phonic wheel **38**. In various embodiments, relative rotation and translation between phonic wheel **38** and sensors **40**A, **40**B may be achieved by having phonic wheel **38** rotatable and translatable relative to sensors **40**A, **40**B, or by having sensors **40**A, **40**B rotatable and translatable relative to phonic wheel **38**.
(24) In reference to FIG. **2**, phonic wheel **38** may be configured to rotate with (e.g., be mechanically coupled to) bladed rotor **12** about rotation axis RA. For example, in some embodiments, phonic wheel **38** may be configured to rotate at the same rotational speed and be coaxial with bladed rotor **12**. However, the rotation axis of phonic wheel **38** may not necessarily be coaxial with rotation axis RA of bladed rotor **12**. Phonic wheel **38** may be axially displaceable along rotation axis RA to a plurality of axial positions as a function of the pitch angle of blades **32**. Accordingly, an axial position of phonic wheel **38** may correspond to a pitch angle of blades **32**. In some embodiments, phonic wheel **38** may be operatively (e.g., mechanically) coupled to bladed rotor **12** as described in US Patent Publication No. 2015/0139798 A1 (title: SYSTEM AND METHOD FOR ELECTRONIC PROPELLER BLADE ANGLE POSITION FEEDBACK), which is incorporated herein by reference.
(25) Phonic wheel **38** may include circumferentially-spaced apart teeth **44**A-**44**C useful for detecting the axial position of phonic wheel **38** as phonic wheel **38** and bladed rotor **12** rotate. Phonic wheel **38** may consequently be useful for detecting pitch angle **52** of adjustable blades **32** by way of a correlation. Phonic wheel **38** may include (e.g., annular) body **46** (e.g., ring) with teeth **44**A-**44**C attached thereto and protruding radially therefrom. In some embodiments, teeth **44**A-**44**C and sensors **40**A, **40**B may be disposed radially outwardly of body **46**. Alternatively, teeth **44**A-**44**C and sensors **40**A, **40**B may be disposed radially inwardly of body **46** instead.
(26) In various embodiments, teeth **44**A-**44**C may be configured such that a passage of teeth **44**A-**44**C can be detected by sensors **40**A, **40**B as phonic wheel **38** rotates about rotation axis RA. In some embodiments, one or more teeth **44**A-**44**C may be separate components individually attached (e.g., fastened) to body **46** of phonic wheel **38**. In some embodiments, one or more teeth **44**A-**44**C may be integrally formed with annular body **46** so that phonic wheel **38** may have a unitary construction. Teeth **44**A-**44**C may include one or more inclined teeth **44**A and one or more reference teeth **44**B, **44**C. In some embodiments, phonic wheel **38** may include a plurality of inclined teeth **44**A all having the same geometric configuration. Inclined teeth **44**A and reference teeth **44**B, **44**C may have different geometric configurations.
(27) Sensors **40**A, **40**B may be inductive (e.g., magnetic, proximity) sensors suitable for non-contact detection of the passage of teeth **44**A-**44**C as phonic wheel **38** rotates about rotation axis RA. Sensors **40**A, **40**B may be mounted adjacent phonic wheel **38** and attached (e.g., fastened) to some stationary structure **41** of engine **10**. In some embodiments, sensors **40**A, **40**B may be configured as Hall effect sensors. In some embodiments, sensors **40**A, **40**B may be configured as variable reluctance sensors (commonly called VR sensors) suitable for detecting the proximity of (e.g., ferrous) teeth **44**A-**44**C. Sensors **40**A, **40**B may each be of a same type. In some embodiments, sensors **40**A, **40**B may each be of a type disclosed in US Patent Publication No. 2018/0304991 A1 (title: FEEDBACK SYSTEM FOR PITCH-ADJUSTABLE BLADES OF AIRCRAFT BLADED ROTOR), which is incorporated herein by reference. In some embodiments, sensors **40**A, **40**B may each be a variable reluctance speed sensor such as model number E58A25 sold under the trade name JAQUET. Sensors **40**A, **40**B may each include an iron core, an inductive coil and a permanent magnet housed in a sensor housing. In some embodiments, sensors **40**A, **40**B may be of a type known as passive or electromagnetic sensors which do not require an external

power supply.

(28) The passing of ferrous teeth **44**A-**44**C by sensor faces **48**A, **48**B may cause a change in the magnetic field strength, resulting in an alternating current (AC) voltage being induced in the coil and output as sensor signals **50**A-**50**C. The change in magnetic field strength may be caused by teeth **44**A-**44**C intersecting the magnetic fields respectively generated and/or detected by sensors **40**A, **40**B as phonic wheel **38** rotates. For example, the passage of each tooth **44**A-**44**C by the sensor faces **48**A, **48**B may cause a change in magnetic permeability within the magnetic fields generated by sensors **40**A, **40**B and consequently cause detectable sensor signals **50**A-**50**C. The frequency of sensor signals **50**A-**50**C may be proportional to rotational speed **56** of phonic wheel **38**. In some embodiments, computer **42** may also determine rotational speed **56** of phonic wheel **38**, **138** based on the frequency of one or more sensor signals **50**A-**50**C. The amplitude of sensor signals **50**A-**50**C may be dependent on (i.e., indicative of) rotational speed **56**, the size of air gaps G**1**, G**2** (shown in FIG. **4**A, **4**B), the geometry of teeth **44**A-**44**C and magnetic properties of the material of phonic wheel **38** for example. Depending on the type of sensor(s) and phonic wheel arrangement, the magnetic field me be generated by the phonic wheel instead of the sensor(s).

(29) Computer **42** may be operatively connected to sensors **40**A, **40**B for receiving one or more of sensor signals **50**A-**50**C and configured to generate one or more outputs (e.g., signals) indicative of pitch angle **52** of adjustable blades **32**, axial position **54** of phonic wheel **38** and/or rotation speed **56** of phonic wheel **38**. In various embodiments, sensors **40**A, **40**B may be in wired or wireless communication with computer **42**. In various embodiments, computer **42** may be part of a Full Authority Digital Engine Control (FADEC) which may, for example, include one or more digital computer(s) or other data processors, sometimes referred to as electronic engine controller(s) (EEC) and related accessories that control at least some aspects of performance of engine **10**. Accordingly, computer **42** may include one or more computing devices including, but not limited to, a digital computer, a processor (e.g. a microprocessor), and a memory. In some embodiments, system **36** may be referred to as an “Np/beta” feedback system where Np represents rotational speed **56** of bladed rotor **12** and beta represents pitch angle **52** of blades **32**. In some embodiments, computer **42** may perform other tasks associated with engine **10**.

(30) FIG. **2**A shows an exemplary perspective view of inclined tooth **44**A. Inclined tooth **44**A may be attached to body **46** and may extend generally axially. Inclined tooth **44**A may include top surface **58**A facing radially outwardly from rotation axis RA. Inclined tooth **44**A may have an axially non-uniform radial height from body **46** and/or from rotation axis RA so that inclined tooth **44**A may have a first (e.g., minimum) radial height Hmin at a first axial position and a different second (e.g., maximum) radial height Hmax at a second axial position. In some embodiments, top surface **58**A of inclined tooth **44**A may be linearly sloped over an axial distance of inclined tooth **44**A and top surface **58**A may be planar. In some embodiments, line L**1** extending axially and lying in a plane of top surface **58**A of inclined tooth **44**A may be inclined relative to rotation axis RA. Line L**1** may also lie in a same plane as rotation axis RA. In other words, line L**1** may lie in a plane that is parallel and coincident with rotation axis RA. In embodiments where top surface **58**A is planar, line L**1** may be a linear segment. In other embodiments where top surface **58**A is non-linearly sloped over the axial distance and line L**1** may be curved.

(31) FIG. **2**B shows an exemplary perspective view of reference tooth **44**B. Reference tooth **44**B may be attached to body **46** and may extend generally axially. Reference tooth **44**B may include top surface **58**B facing radially outwardly from rotation axis RA. Reference tooth **44**B may have an axially uniform radial height corresponding to maximum radial height Hmax from body **46** and/or from rotation axis RA. Top surface **58**B of reference tooth **44**B may be planar. In some embodiments, line L**2** extending axially and lying in a plane of top surface **58**B of inclined tooth **44**A may be parallel to rotation axis RA. Line L**2** may lie in a same plane as rotation axis RA. In other words, line L**2** may lie in a plane that is parallel and coincident with rotation axis RA. Line L**2** may be a linear segment.

(32) In some embodiments, reference tooth **44**B may alternatively have an axially uniform radial height corresponding to minimum radial height Hmin from body **46** and/or from rotation axis RA. In some embodiments, reference tooth **44**B may have an axially uniform radial height that is between minimum radial height Hmin and maximum radial height Hmax. In some embodiments, phonic wheel **38** may include two reference teeth **44**B, **44**C where reference tooth **44**B has an axially uniform radial height corresponding to maximum radial height Hmax and reference tooth **44**C has an axially uniform radial height corresponding to minimum radial height Hmin. Reference tooth **44**C may have the same configuration as reference tooth **44**B except for having a smaller axially uniform radial height Hmin. In various embodiments, phonic wheel **38** may include one or more inclined teeth **44**A and one or more reference teeth **44**B, **44**C circumferentially distributed around body **46** of phonic wheel **38**.
(33) Phonic wheel **38** may define troughs **60** between adjacent inclined teeth **44**A. The bottoms of troughs **60** may be respectively defined by a surface of body **46** adjacent inclined teeth **44**A. In some embodiments, troughs **60** may be parallel to rotation axis RA so that inclined teeth **44**A may have an axially non-uniform radial height from the surface of body **46**.
(34) FIG. **3** is a partial schematic representation of another exemplary phonic wheel **138** that may be part of system **36** instead of phonic wheel **38**. Phonic wheel **138** may have elements in common with phonic wheel **38**. Like elements have been identified with like reference numerals that have been incremented by **100**. In contrast with phonic wheel **38**, phonic wheel **138** may define troughs **160** between adjacent inclined teeth **144**A. The bottoms of troughs **160** may be respectively defined by a surface of body **146** adjacent inclined teeth **144**A. In some embodiments, troughs **160** may be axially inclined relative to rotation axis RA. In some embodiment, the inclination of troughs **160** may be the same as their adjacent inclined teeth **144**A so that inclined teeth **144**A may have an axially uniform radial height from the surface of body **146** but may have an axially non-uniform radial height from rotation axis RA.
(35) In some embodiments, inclined troughs **160** may cause the same geometry of inclined tooth **144**A to be presented to inclined sensor **40**A at different relative axial positions even though gap G**1** may change as a function of axial position. In some situations, presenting the same tooth geometry to inclined sensor **40**A may further improve compatibility between positioning sensor signal **50**A obtained from inclined sensor **40**A from the passage of inclined tooth **144**A and reference sensor signal(s) **50**B and **50**C obtained from reference sensor **40**B from the passage of reference teeth **144**B and **144**C respectively.
(36) FIG. **4**A is a partial schematic cross-section view showing part of phonic wheel **138** of FIG. **3** above rotation axis RA taken along line **4**A-**4**A in FIG. **3**. The following explanation may also apply to phonic wheel **38**. Phonic wheel **138** may be rotatable about rotation axis RA and axially translatable along rotation axis RA (e.g., see arrow A). Phonic wheel **138** may include one or more inclined teeth **144**A having substantially identical geometries. Inclined tooth **144**A shown may have top surface **158**A having an axially non-uniform radial height from maximum radial height Hmax to minimum radial height Hmin from rotation axis RA. In some embodiments, minimum radial height Hmin of top surface **158**A from rotation axis RA may correspond to a first axial position (e.g., displacement limit) for phonic wheel **138**, and maximum radial height Hmax of top surface **158**A from rotation axis RA may correspond to a second axial position (e.g., displacement limit) for phonic wheel **138**. In some embodiments, the axial positions of maximum radial height Hmax and minimum radial height Hmin along rotation axis RA may define the range of axial travel of phonic wheel **138** during operation.
(37) Inclined sensor **40**A may be tilted so as to be non-perpendicular to rotation axis RA. Inclined sensor **40**A may have sensor axis SA**1** that may be inclined relative to orientation P perpendicular to rotation axis RA. In other words, sensor axis SA**1** of inclined sensor **40**A may be non-perpendicular to rotation axis RA. Sensor axis SA**1** may be an orientation along which gap G**1** between sensor face **48**A and top surface **158**A of tooth **144**A is intended to be measured with

inclined sensor **40**A. For example, sensor axis SA**1** may pass through a center of sensor face **48**A and extend perpendicularly to sensor face **48**A. In case of a variable reluctance sensor, sensor axis SA**1** may correspond to an axis of symmetry of the magnetic field generated by the magnet of inclined sensor **40**A without external influence. Sensor axis SA**1** may correspond to a central axis about which the induction coil of inclined sensor **40**A is wound. In some embodiments, sensor axis SA**1** may correspond to a central/longitudinal axis of the magnet of inclined sensor **40**A. In some embodiments, sensor axis SA**1** may correspond to a central/longitudinal axis of a cylindrical housing of inclined sensor **40**A.

(38) The orientation of inclined sensor **40**A may be based on the orientation of top surface **158**A of inclined tooth **144**A. For example, in situations where top surface **158**A is linearly sloped, inclined sensor **40**A may be oriented to be perpendicular to top surface **158**A (and of line L**1** shown in FIG. **2**) so that angle B**1** may be about 90 degrees. In some embodiments, the perpendicular orientation of inclined sensor **40**A relative to top surface **158**A may promote a uniform gap G**1** across sensor face **48**A and also promote symmetry of the magnetic field across sensor axis SA**1** when the magnetic field generated by inclined sensor **40**A is influenced by the presence of inclined tooth **44**A. For example, a uniform gap G**1** across sensor face **48**A may reduce skewing of the magnetic field generated by inclined sensor **40**A relative to sensor axis SA**1**. In situations where top surface **158**A is non-linearly sloped, inclined sensor **40**A may be oriented to be perpendicular to an average slope of top surface **158**A for example.

(39) In various embodiments, top surface **158**A of inclined tooth **144**A may be inclined relative to rotation axis RA. For example, in some embodiments, top surface **158**A may be inclined by an angle of between 10 and 20 degrees relative to rotation axis RA. In some embodiments, inclined sensor **40**A may be inclined/tilted by the same amount from orientation P perpendicular to rotation axis RA. The slope and permeability of teeth **44**A-**44**C, **144**A-**144**C may be selected such that at a low speed of phonic wheel **38**, **138** and at maximum air gap G**3** (shown in FIG. **8**), the amplitude of sensor signal **50**C is sufficient to produce a zero crossing and allow for an amplitude determination within a suitable accuracy.

(40) During operation of system **36**, phonic wheel **138** may rotate about rotation axis RA and may also axially translate along rotation axis RA. As phonic wheel **138** is translated relative to inclined sensor **40**A, the size of air gap G**1** may also vary. Inclined tooth **144**A may be sloped axially such that axial translation of phonic wheel **138** causes a gradual change in air gap G**1** between top surface **158**A and sensor face **48**A of inclined sensor **40**A. This change in air gap G**1** may in turn cause the amplitude of positioning sensor signal **50**A (shown in FIG. **2**) to also gradually vary as phonic wheel **138** is axially translated. The amplitude of positioning sensor signal **50**A may therefore be representative of the axial position of phonic wheel **138**. As shown in FIG. **4**A, trough **160** may be axially sloped by the same amount so that inclined tooth **144**A may have an axially uniform height from the surface of body **146**.

(41) FIG. **4**B is a partial schematic cross-section view showing part of phonic wheel **138** of FIG. **3** above rotation axis RA taken along line **4**B-**4**B in FIG. **3**. The following explanation may also apply to phonic wheel **38**. Phonic wheel **138** may include one or more reference teeth **144**B, **144**C. Reference tooth **144**B shown may have top surface **158**B having an axially uniform radial height from rotation axis RA at maximum height Hmax of inclined tooth **144**A. In some embodiments, reference tooth **144**C shown in FIG. **3** may be configured substantially identically to reference tooth **144**B except for having a top surface disposed at an axially uniform radial height from rotation axis RA set to minimum height Hmin of inclined tooth **144**A. Various embodiments of phonic wheel **138** may include reference tooth **144**B, reference tooth **144**C or both reference tooth **144**B and reference tooth **144**C. Reference sensor **40**B may be fixedly mounted relative to inclined sensor **40**A and may also be adjacent to phonic wheel **138**. Sensor axis SA**2** of reference sensor **40**B may be perpendicular to rotation axis RA, to top surface **158**B and also to line L**2** so that angle B**2** may be about 90 degrees.

(42) During operation of system **36**, as phonic wheel **138** is rotated and axially translated relative to reference sensor **40**B, the size of air gap G**2** may remain substantially constant. Reference sensor **40**B may be configured to generate reference sensor signal **50**B indicative of air gap G**2** between top surface **158**B of reference tooth **144**B and reference sensor **40**B along sensor axis SA**2** of reference sensor **40**B as relative rotation and translation between reference sensor **40**B and reference tooth **144**B occurs. In embodiments where both reference teeth **144**B, **144**C are present, the same reference sensor **40**B may be used to provide reference sensor signal **50**B associated with the presence of reference tooth **144**B and reference sensor signal **50**C (shown in FIG. **2**) associated with the presence of reference tooth **144**C as phonic wheel **138** rotates. Reference sensor signal **50**C may be indicative of air gap G**3** (shown in FIG. **8**) between a top surface of reference tooth **144**C and reference sensor **40**B along sensor axis SA**2** of reference sensor **40**B.
(43) Reference sensor signal(s) **50**B, **50**C may respectively define maximum and minimum signal amplitudes that can be expected at the maximum radial height Hmax and at the minimum radial height Hmin of inclined tooth **144**A corresponding to axial travel boundaries of phonic wheel **138**. Accordingly, positioning sensor signal **50**A may be compared with reference sensor signal(s) **50**B, **50**C in order to interpolate an axial position of phonic wheel **138** between the axial travel boundaries. In some embodiments, reference sensor signal(s) **50**B, **50**C may be acquired at each revolution of phonic wheel **138**. In some embodiments, positioning sensor signal **50**A and reference sensor signal(s) **50**B, **50**C may be acquired during the same revolution of phonic wheel **138**.
(44) In some embodiments, inclined sensor **40**A and reference sensor **40**B may be substantially axially aligned so that inaccuracies introduced at the axial ends (also known as “edge effect”) of teeth **44**A-**44**C, **144**A-**144**C may be taken in consideration in reference sensor signal(s) **50**B, **50**C. For example, a center of sensor face **48**A of inclined sensor **40**A may be axially aligned with a center of sensor face **48**B of reference sensor **40**B. In some embodiments, teeth **44**A-**44**C, **144**A-**144**C may be made to extend beyond the axial travel limits of phonic wheel **38**, **138** to reduce or eliminate such edge effect.
(45) FIG. **5** is a schematic representation of an exemplary computer **42** of system **36**. Computer **42** may include one or more data processors **62** (referred hereinafter as “processor **62**”) and non-transitory machine-readable memory **64**. Computer **42** may be configured to regulate the operation of system **36** and optionally also control other aspects of operation of engine **10**. Computer **42** may receive input(s) such as positioning sensor signal(s) **50**A and reference sensor signal(s) **50**B, **50**C, perform one or more procedures or steps defined by instructions stored in memory **64** and executable by processor **62** to generate one or more outputs. Such output(s) may include a pitch angle **52** of blades **32**, axial position **54** of phonic wheel **38**, **138** and/or rotational speed **56** of phonic wheel **38**, **138**.
(46) Processor **62** may include any suitable device(s) configured to cause a series of steps to be performed by computer **42** so as to implement a computer-implemented process such that instructions, when executed by computer **42** or other programmable apparatus, may cause the functions/acts specified in the methods described herein to be executed. Processor **62** may include, for example, any type of general-purpose microprocessor or microcontroller, a digital signal processing (DSP) processor, an integrated circuit, a field programmable gate array (FPGA), a reconfigurable processor, other suitably programmed or programmable logic circuits, or any combination thereof.
(47) Memory **64** may include any suitable machine-readable storage medium. Memory **64** may include non-transitory computer readable storage medium such as, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. Memory **64** may include any storage means (e.g. devices) suitable for retrievably storing machine-readable instructions executable by processor **62**. In some embodiment, memory **64** may store machine-readable instructions in the form of peak detection function **66**, interpolation function **68** and look-up function **70**, which are described

further below.

(48) FIG. **6** is a flow diagram of an exemplary method **1000** for measuring an axial position of phonic wheel **38**, **138**. Method **100** may be performed using system **36** described herein or using other system(s). For example, computer **42** may be configured to perform at least part of method **1000**. Aspects of method **1000** may be combined with aspects of other methods or actions described herein. Method **1000** may include elements of system **36**. In various embodiments, method **1000** may include: directing a first magnetic field from inclined sensor **40**A toward a location that inclined tooth **44**A, **144**A of phonic wheel **38**, **138** is expected to occupy as phonic wheel **38**, **138** rotates relative to inclined sensor **40**A about rotation axis RA, inclined tooth **44**A, **144**A extending axially relative to rotation axis RA and having an axially non-uniform height, inclined sensor **40**A being inclined relative to orientation P perpendicular to rotation axis RA (block **1002**); detecting a variation in the first magnetic field caused by movement of inclined tooth **44**A, **144**A in the first magnetic field (block **1004**); generating a first feedback signal (e.g., positioning sensor signal **50**A) based on the detection of the variation in the first magnetic field (block **1006**); directing a second magnetic field from reference sensor **40**B toward a location that reference tooth **44**B, **144**B of phonic wheel **38**, **138** is expected to occupy as phonic wheel **38**, **138** rotates relative to reference sensor **40**B about rotation axis RA, reference tooth **44**B, **144**B extending axially relative to rotation axis RA and having an axially uniform height (block **1008**); detecting a variation in the second magnetic field caused by movement of (e.g., non-inclined) reference tooth **44**B, **144**B in the second magnetic field (block **1010**); generating a second feedback signal (e.g., reference sensor signal **50**B) based on the detection of the variation in the second magnetic field (block **1012**); and generating an output indicative of the axial position **54** of phonic wheel **38**, **138** based on the first feedback signal and the second feedback signal (block **1014**).

(49) In some embodiments, method **1000** may include: directing the second magnetic field from reference sensor **40**B toward a location that reference tooth **44**C, **144**C of phonic wheel **38**, **138** is expected to occupy as phonic wheel **38**, **138** rotates relative to reference sensor **40**B about rotation axis RA, reference tooth **44**C, **144**C extending axially relative to rotation axis RA and having an axially uniform height different from the height of reference tooth **44**B, **144**B; detecting a variation in the second magnetic field caused by movement of reference tooth **44**C, **144**C in the second magnetic field; generating a third feedback signal (e.g., reference sensor signal **50**C) based on the detection of the variation in the second magnetic field caused by movement of reference tooth **44**C, **144**C in the second magnetic field; and generating the output indicative of the axial position **54** of phonic wheel **38**, **138** based on the first feedback signal, the second feedback signal and the third feedback signal.

(50) Further aspects of method **1000** are described below in relation to FIGS. **7-9**.

(51) FIG. **7** is a flow diagram illustrating aspects of method **1000**. FIG. **7** illustrates an embodiment where two reference teeth **44**B, **44**C, **144**B, **144**C are used but embodiments of method **1000** may use only one reference tooth **44**B, **44**C, **144**B, **144**C. During a revolution of phonic wheel **38**, **138**, computer **42** may receive reference sensor signals **50**B, **50**C instantaneously generated by reference sensor **40**B from the passing of reference teeth **44**B, **44**C, **144**B, **144**C by reference sensor **40**B. During the same or other revolution of phonic wheel **38**, **138**, computer **42** may also receive positioning sensor signal **50**A instantaneously generated by inclined sensor **40**A from the passing of inclined tooth **44**A by inclined sensor **40**A. Sensor signals **50**A-**50**C may be time-varying voltages having a sinusoidal shape for example. Peak detection function **66** may process sensor signals **50**A, **50**B, **50**C and output respective (e.g., peak to peak or root-mean-square (RMS)) amplitudes of sensor signals **50**A-**50**C. Based on the known relative positioning (i.e., known sequence on phonic wheel **38**, **138**) of inclined tooth or teeth **44**A, **144**A and reference tooth or teeth **44**B, **44**C, **144**B, **144**C and the amplitudes detected, peak detection function **66** may discriminate sensor signals **50**A-**50**C. Specifically, positioning sensor signal **50**A associated with inclined tooth **44**A, **144**A may be processed to obtain positioning amplitude **72**A, reference sensor signal **50**B associated with

reference tooth **44**B, **144**B may be processed to obtain maximum reference amplitude **72**B, and reference sensor signal **50**C associated with reference tooth **44**C, **144**C may be processed to obtain minimum reference amplitude **72**C.

(52) Amplitudes **72**A-**72**C may then be provided to interpolation function **68**, which may be used to determine air gap G**1** between inclined sensor **40**A and inclined tooth **44**A, **144**A. Using look-up function **70**, a corresponding axial position **54** of phonic wheel **38**, **138** may be associated with air gap G**1**.

(53) FIG. **8** is a graph of a relationship **74** between the amplitudes **72**A-**72**B of sensor signals **50**A-**50**C and corresponding air gaps G**1**, G**2**, G**3**. Relationship **74** is shown as being linear for the sake of clarity but relationship **74** may be non-linear (e.g., semi-logarithmic). Maximum reference amplitude **72**B and minumum reference amplitude **72**C may be associated with respective predetermined values of air gaps G**2** and G**3** that may be stored in memory **64** of computer **42**. For example, values of air gaps G**2** and G**3** may have been determined during a design stage of system **36** or during an installation or setup of system **36**. Method **1000** may include associating maximum reference amplitude **72**B of reference sensor signal **50**B to reference air gap G**2** and associating minimum reference amplitude **72**C of reference signal **50**C to reference air gap G**3**. With relationship **74**, interpolation may then be used to determine air gap G**1** between inclined tooth **44**A, **144**A and inclined sensor **40**A between reference air gaps G**2** and G**3** based on positioning amplitude **72**A. In some embodiments, determining the value of air gap G**1** may be done by solving an equation defining relationship **74** using positioning amplitude **72**A, maximum reference amplitude **72**B and/or minimum reference amplitude **72**C.

(54) In some embodiments, the amplitudes **72**A-**72**C of sensor signals **50**A-**50**C may depend on rotational speed **56**. However since reference sensor signals **50**B, **50**C respectively associated with known air gaps G**2**, G**3** are acquired together with positioning signal **50**A, rotational speed **56** may not need to be known to determine air gap G**1**. Since all sensor signals **50**A-**50**C may be acquired at the same rotational speed of phonic wheel **38**, **138**, interpolation may be used to determine air gap G**1** without the need of rotational speed **56**. In other words, determining air gap G**1** may include comparing positioning sensor signal **50**A with one or more of reference sensor signals **50**B, **50**C. For example, positioning amplitude **72**A may be compared to maximum reference amplitude **72**B and/or to minimum reference amplitude **72**C to determine air gap G**1** in relation to one or both of reference air gaps G**2** and G**3**.

(55) For example, even though FIG. **8** illustrates an interpolation between maximum reference amplitude **72**B and minimum reference amplitude **72**C to determine air gap G**1**, a single reference amplitude may be sufficient to determine air gap G**1** with the knowledge of relationship **74** by comparison of positioning amplitude **72**A with the single reference amplitude.

(56) FIG. **9** is a table defining a relationship between values (e.g., GAP**1**-GAP**6**) of air gap G**1**, values (e.g., A**1**-A**6**) of axial position **54** of phonic wheel **38**, **138** and optionally values (e.g., P**1**-P**6**) of pitch angle **52** of bladed rotor **32**. Look-up function **70** may use a look-up table or other relationship to associate (relate) air gap G**1** to axial position **54** of phonic wheel **38**, **138**. Look-up function **70** may instead or in addition relate air gap G**1** to pitch angle **52** of bladed rotor **32**. Look-up function **70** may relate axial position **54** of phonic wheel **38**, **138** to pitch angle **52** of blades **32** of bladed rotor **12**.

(57) The embodiments described in this document provide non-limiting examples of possible implementations of the present technology. Upon review of the present disclosure, a person of ordinary skill in the art will recognize that changes may be made to the embodiments described herein without departing from the scope of the present technology. Yet further modifications could be implemented by a person of ordinary skill in the art in view of the present disclosure, which modifications would be within the scope of the present technology.

Claims

1. A system for measuring an axial position of a phonic wheel, the system comprising: the phonic wheel rotatable about a rotation axis and translatable along the rotation axis, the phonic wheel including: a body; an inclined tooth attached to the body and extending axially, a top surface of the inclined tooth being inclined relative to the rotation axis; and a reference tooth attached to the body and extending axially, a top surface of the reference tooth being parallel to the rotation axis; an inclined sensor adjacent the phonic wheel and configured to generate a positioning signal indicative of a gap between the top surface of the inclined tooth and the inclined sensor along a sensor axis of the inclined sensor as the phonic wheel is rotated relative to the inclined sensor, the sensor axis of the inclined sensor being non-perpendicular to the rotation axis; a reference sensor adjacent the phonic wheel and configured to generate a reference signal indicative of a gap between the top surface of the reference tooth and the reference sensor along a sensor axis of the reference sensor as the phonic wheel is rotated relative to the reference sensor, the sensor axis of the reference sensor being perpendicular to the rotation axis; and a computer operatively connected to the inclined sensor and to the reference sensor, the computer being configured to generate an output indicative of the axial position of the phonic wheel based on the positioning signal and the reference signal.
2. The system as defined in claim 1, wherein: the top surface of the inclined tooth is linearly sloped over an axial distance of the inclined tooth; and the sensor axis of the inclined sensor is perpendicular to the top surface of the inclined tooth.
3. The system as defined in claim 1, wherein the computer is configured to: based on a comparison of the positioning signal to the reference signal, determine the gap between the top surface of the inclined tooth and the inclined sensor; and associate the gap between the top surface of the inclined tooth and the inclined sensor to the axial position of the phonic wheel.
4. The system as defined in claim 1, wherein: the top surface of the inclined tooth has a minimum radial height from the rotation axis corresponding to a first axial position for the phonic wheel, and a maximum radial height from the rotation axis corresponding to a second axial position for the phonic wheel; and the top surface of the reference tooth is at the minimum radial height from the rotation axis or at the maximum radial height from the rotation axis.
5. The system as defined in claim 4, wherein: the reference tooth is a first reference tooth, the top surface of the first reference tooth being at the minimum radial height from the rotation axis; and the phonic wheel includes a second reference tooth attached to the body and extending axially, a top surface of the second reference tooth being parallel to the rotation axis and at the maximum radial height from the rotation axis.
6. The system as defined in claim 5, wherein: the reference signal is a first reference signal; the reference sensor is configured to generate a second reference signal indicative of a gap between the top surface of the second reference tooth and the reference sensor along the sensor axis of the reference sensor as the phonic wheel is rotated relative to the reference sensor; and the computer is configured to generate the output indicative of the axial position of the phonic wheel based on the positioning signal, the first reference signal and the second reference signal.
7. The system as defined in claim 6, wherein the computer is configured to: based on a comparison of an amplitude of the positioning signal to an amplitude of the first reference signal and to an amplitude of the second reference signal, determine the gap between the top surface of the inclined tooth and the inclined sensor; and use the gap between the top surface of the inclined tooth and the inclined sensor to determine the axial position of the phonic wheel.
8. The system as defined in claim 6, wherein the computer is configured to: associate an amplitude of the first reference signal to a first reference gap value; associate an amplitude of the second reference signal to a second reference gap value; and use interpolation to determine the gap between the top surface of the inclined tooth and the inclined sensor between the first reference gap

value and the second reference gap value using an amplitude of the positioning signal.
9. The system as defined in claim 1, wherein a surface of the body adjacent the inclined tooth is parallel to the rotation axis so that the inclined tooth has an axially non-uniform radial height from the surface of the body.
10. The system as defined in claim 1, wherein a surface of the body adjacent the inclined tooth is axially inclined relative to the rotation axis so that the inclined tooth has an axially uniform radial height from the surface of the body.
11. The system as defined in claim 1, wherein the inclined sensor and the reference sensor are both variable reluctance sensors.
12. An aircraft engine comprising: a bladed rotor rotatable about a rotation axis and having pitch-adjustable blades; a toothed ring coaxial with the rotation axis, the toothed ring including: an inclined tooth extending axially relative to the rotation axis and having an axially non-uniform radial height; and a reference tooth extending axially relative to the rotation axis and having an axially uniform radial height; an inclined sensor adjacent to the toothed ring, the toothed ring being rotatable about the rotation axis and translatable axially along the rotation axis as a function of a pitch angle of the pitch-adjustable blades, the inclined sensor being configured to generate a positioning signal indicative of a gap between the inclined tooth and the inclined sensor along a sensor axis of the inclined sensor as rotation of the toothed ring relative to the inclined sensor occurs, the sensor axis of the inclined sensor being perpendicular to a top surface of the inclined tooth; a reference sensor fixedly mounted relative to the inclined sensor and adjacent to the toothed ring, the reference sensor being configured to generate a reference signal indicative of a gap between the reference tooth and the reference sensor along a sensor axis of the reference sensor as rotation of the toothed ring relative to the reference sensor occurs, the sensor axis of the reference sensor being perpendicular to the rotation axis; and a computer operatively connected to the inclined sensor and to the reference sensor, the computer being configured to generate an output indicative of a relative axial position between the toothed ring and the inclined sensor based on the positioning signal and the reference signal.
13. The aircraft engine as defined in claim 12, wherein the inclined sensor is disposed radially outwardly of the toothed ring.
14. The aircraft engine as defined in claim 12, wherein: the top surface of the inclined tooth has a minimum radial height from the rotation axis and a maximum radial height from the rotation axis; and a top surface of the reference tooth is at the minimum radial height from the rotation axis or at the maximum radial height from the rotation axis.
15. The aircraft engine as defined in claim 14, wherein: the reference tooth is a first reference tooth, the top surface of the first reference tooth being at the minimum radial height from the rotation axis; and the toothed ring includes a second reference tooth extending axially relative to the rotation axis, the second reference tooth having an axially uniform radial height at the maximum radial height from the rotation axis.
16. The aircraft engine as defined in claim 15, wherein: the reference signal is a first reference signal; the reference sensor is configured to generate a second reference signal indicative of a gap between the second reference tooth and the reference sensor along the sensor axis of the reference sensor as rotation of the toothed ring relative to the reference sensor occurs; and the computer is configured to generate the output indicative of the relative axial position between the toothed ring and the inclined sensor based on the positioning signal, the first reference signal and the second reference signal.
17. The aircraft engine as defined in claim 16, wherein the computer is configured to: associate an amplitude of the first reference signal to a first reference gap value; associate an amplitude of the second reference signal to a second reference gap value; and use interpolation to determine the gap between the inclined tooth and the inclined sensor between the first reference gap value and the second reference gap value using an amplitude of the positioning signal.

18. The aircraft engine as defined in claim 17, wherein a surface of the toothed ring adjacent the inclined tooth is axially inclined relative to the rotation axis so that the inclined tooth has an axially uniform radial height from the surface of the toothed ring.

19. A method for measuring an axial position of a phonic wheel, the method comprising: directing a first magnetic field from a first sensor toward a location that a first tooth of the phonic wheel is expected to occupy as the phonic wheel rotates about a rotation axis relative to the first sensor, the first tooth extending axially relative to the rotation axis and having an axially non-uniform radial height, the first sensor being inclined relative to an orientation perpendicular to the rotation axis; detecting a variation in the first magnetic field caused by movement of the first tooth in the first magnetic field; generating a first feedback signal based on the detection of the variation in the first magnetic field; directing a second magnetic field from a second sensor toward a location that a second tooth of the phonic wheel is expected to occupy as the phonic wheel rotates relative to the second sensor about the rotation axis, the second tooth extending axially relative to the rotation axis and having an axially uniform radial height; detecting a variation in the second magnetic field caused by movement of the second tooth in the second magnetic field; generating a second feedback signal based on the detection of the variation in the second magnetic field; and generating an output indicative of the axial position of the phonic wheel based on the first feedback signal and the second signal.

20. The method as defined in claim 19, comprising: directing the second magnetic field from the second sensor toward a location that a third tooth of the phonic wheel is expected to occupy as the phonic wheel rotates relative to the second sensor about the rotation axis, the third tooth extending axially relative to the rotation axis and having an axially uniform radial height different from the radial height of the second tooth; detecting a variation in the second magnetic field caused by movement of the third tooth in the second magnetic field; generating a third feedback signal based on the detection of the variation in the second magnetic field caused by movement of the third tooth in the second magnetic field; and generating the output indicative of the axial position of the phonic wheel based on the first feedback signal, the second feedback signal and the third feedback signal.