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Accretion detection systems and associated methods for gas turbine engines

Abstract

An assembly for a gas turbine engine according to an example of the present disclosure may include at least one rotatable airfoil, at least one vibration sensor operable to detect vibration of the at least one airfoil at one or more rotational frequencies, and a controller operatively coupled to the at least one vibration sensor. The controller may be operable to determine an accretion level associated with accretion of glass on the at least one airfoil in response to comparing vibration of the at least one airfoil at the one or more rotational frequencies to a vibratory pattern associated with accretion of glass. A method of operation is also disclosed.

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References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
4335600	12/1981	Wu et al.	N/A	N/A
9327839	12/2015	Giles et al.	N/A	N/A
10385723	12/2018	Flynn et al.	N/A	N/A
11702939	12/2022	Riverin	N/A	N/A
2002/0059831	12/2001	Naudet	73/579	G01N 29/46
2007/0194773	12/2006	Dankert et al.	N/A	N/A

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
1024951	12/2017	BE	N/A

OTHER PUBLICATIONS

European Search Report for European Patnet Application No. 24195628.3 mailed Jan. 23, 2025. cited by applicant

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Background/Summary

BACKGROUND

(1) This disclosure relates to detecting a condition of gas turbine engine components.

(2) Gas turbine engines may include a fan for propulsion air. The fan may also deliver air into a core engine where it is compressed. The compressed air is then delivered into a combustion section, where it is mixed with fuel and ignited. The combustion gas expands downstream over and drives turbine blades.

(3) The engine may ingest particulates during operation in various environmental conditions, which may be deposited on surface of the components.

SUMMARY

(4) An assembly for a gas turbine engine according to an example of the present disclosure may include at least one rotatable airfoil, at least one vibration sensor operable to detect vibration of the at least one airfoil at one or more rotational frequencies, and a controller operatively coupled to the at least one vibration sensor. The controller may be operable to determine an accretion level associated with accretion of glass on the at least one airfoil in response to comparing vibration of the at least one airfoil at the one or more rotational frequencies to a vibratory pattern associated

with accretion of glass.

(5) In a further embodiment of any of the foregoing embodiments, the controller may be operable to cause an indicator to be generated in response to determining that the accretion level meets an accretion threshold.

(6) In a further embodiment of any of the foregoing embodiments, the controller may be operable to determine a brittleness characteristic associated with accretion of glass based on the accretion level.

(7) In a further embodiment of any of the foregoing embodiments, the controller may be operable to cause excitation of the at least one airfoil to release debris associated with the accretion level in response to determining that the accretion level meets an accretion threshold.

(8) In a further embodiment of any of the foregoing embodiments, the controller may be operable to cause excitation of the at least one airfoil in response to causing a rotational speed of the at least one airfoil to approach a resonant frequency of the at least one airfoil.

(9) In a further embodiment of any of the foregoing embodiments, the vibratory pattern may be associated with the one or more rotational frequencies and one or more respective vibration thresholds.

(10) In a further embodiment of any of the foregoing embodiments, the controller may be operable to determine the accretion level in response to comparing at least one amplitude associated with vibration of the at least one airfoil at the respective rotational frequency to the respective vibration threshold. The vibratory pattern may be established based on different amounts of accretion of glass and associated vibration for each of the amounts of accretion of glass at the rotational frequencies.

(11) In a further embodiment of any of the foregoing embodiments, the one or more rotational frequencies may include a plurality of rotational frequencies associated with the vibratory pattern. The one or more vibration thresholds may include a plurality of vibration thresholds associated with the respective rotational frequencies. The at least one amplitude may include a plurality of amplitudes associated with the respective rotational frequencies. The controller may be operable to determine the accretion level in response to determining that the amplitudes meet the respective vibration thresholds.

(12) In a further embodiment of any of the foregoing embodiments, the controller may be operable to determine the accretion level in response to determining a best fit of vibration at the one or more rotational frequencies to a set of vibratory responses associated with the vibratory pattern and respective amounts of accretion.

(13) In a further embodiment of any of the foregoing embodiments, at least one airfoil may be propulsor blade for generating thrust.

(14) A gas turbine engine according to an example of the present disclosure may include a propulsor section including a propulsor, a compressor, a turbine that drives the propulsor, a plurality of airfoils rotatable about an engine axis, at least one vibration sensor operable to generate a signal associated with vibration of one or more of the airfoils at one or more rotational frequencies, and a controller operatively coupled to the at least one vibration sensor. The controller may be operable to determine an accretion condition associated with glass accretion on the one or more respective airfoils in response to comparing the signal to a vibratory pattern.

(15) In a further embodiment of any of the foregoing embodiments, the one or more rotational frequencies may include a plurality of rotational frequencies associated with rotation of the airfoils about the engine axis. The vibratory pattern may be associated with the rotational frequencies and a plurality of respective vibration thresholds. The controller may be operable to determine the accretion condition in response to comparing an amplitude associated with the signal to the vibration threshold associated with the respective rotational frequency.

(16) In a further embodiment of any of the foregoing embodiments, the controller may be operable to cause excitation of one or more of the airfoils to remove glass on the one or more respective

airfoils in response to determining the accretion condition.
(17) In a further embodiment of any of the foregoing embodiments, the controller may be operable to cause a change in a rotational speed of the airfoils such that the rotational speed approaches a resonant frequency of the airfoils.
(18) A method of operation associated with a gas turbine engine according to an example of the present disclosure may include establishing a vibratory pattern based on accretion of glass at one or more rotational frequencies, determining vibration of a rotatable airfoil at the one or more rotational frequencies, and determining an accretion of glass on the airfoil in response to comparing the determined vibration to the vibratory pattern.
(19) In a further embodiment of any of the foregoing embodiments, determining the vibration may include determining one or more amplitudes associated with the vibration at the one or more rotational frequencies.
(20) In a further embodiment of any of the foregoing embodiments, establishing the the vibratory pattern may include establishing one or more vibration thresholds associated with accretion of glass at the one or more respective rotational frequencies. Determining the accretion may include determining that the one or more amplitudes meet the one or more respective vibration thresholds.
(21) A further embodiment of any of the foregoing embodiments may include generating an indicator in response to determining the accretion.
(22) A further embodiment of any of the foregoing embodiments may include exciting the airfoil to release at least a portion of the glass from the airfoil in response to determining the accretion.
(23) In a further embodiment of any of the foregoing embodiments, exciting the airfoil may include changing a rotational speed of the airfoil such that the rotational speed approaches a resonant frequency of the airfoil.
(24) The present disclosure may include any one or more of the individual features disclosed above and/or below alone or in any combination thereof.
(25) The various features and advantages of this disclosure will become apparent to those skilled in the art from the following detailed description. The drawings that accompany the detailed description can be briefly described as follows.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** schematically illustrates a gas turbine engine.
(2) FIG. **2** discloses a detection system for a gas turbine engine.
(3) FIG. **3** discloses a section of a gas turbine engine.
(4) FIGS. **4**A-**4**C disclose plots associated with accretion of debris on a component.
(5) FIG. **5** discloses a plot associated with brittleness of debris on a component.
(6) FIG. **6** discloses a method of operation associated with detecting accretion of debris on a component.
(7) Like reference numbers and designations in the various drawings indicate like elements.
DETAILED DESCRIPTION
(8) Disclosed are techniques for detecting the accretion of glass and/or other debris that may be disposed on surfaces of gas turbine engine components. The disclosed techniques may be utilized for prognostics and diagnostics to improve the performance and durability of the components, including during flight and/or maintenance. Debris may be ingested by an associated engine during operation in various environmental conditions. The debris may bond or otherwise accumulate on the component surfaces. The debris may form into glass on the surfaces due to heat exposure.
(9) A detection system may be operable to detect the presence and/or amount of accretion of glass and/or other debris on surfaces of the component, such as a rotatable airfoil (e.g., blade). The

system may be operable to compare a blade-pass vibratory mode relative to a baseline non-accreted blade to perform the determination. A model may be representative of a state of the glass (e.g., brittleness). The system may be operable interact with one or more sensors and/or aircraft systems to track or otherwise monitor conditions associated with glass accretion (e.g., dust ingestion, temperature, and pressure). The sensor(s) may include one or more vibration sensors positioned adjacent to the components. The system may be operable to determine the state of the glass and/or debris based on the determined conditions. The accumulation of glass and/or other debris may cause a change in flutter frequency of the component. The system may be operable to determine the change in flutter frequency. In implementations, the system may be operable to correlate an amount of glass to a vibratory response pattern as measured by the vibration sensor(s). The system may be operable to cause a change in the condition of components associated with the detected accretion. In implementations, the system may be operable to cause excitation of the airfoil near a predetermined blade mode (e.g., resonant frequency) to induce short term flutter to relieve the airfoil of the accumulated glass and/or other debris. The system may be operable to determine an amplitude of the blade frequency subsequent to the excitation for determining the effectiveness of the shedding. Exciting the component may occur over one or more intervals during the same flight cycle (e.g., in flight) and/or maintenance cycle or may occur for fewer than each flight and/or maintenance cycle of the engine.
(10) FIG. **1** schematically illustrates a gas turbine engine **20**. The gas turbine engine **20** is disclosed herein as a two-spool turbofan that generally incorporates a fan section **22**, a compressor section **24**, a combustor section **26** and a turbine section **28**. The fan section **22** may include a single-stage fan **42** having a plurality of fan blades **43**. The fan blades **43** may have a fixed stagger angle or may have a variable pitch to direct incoming airflow from an engine inlet. The fan **42** drives air along a bypass flow path B in a bypass duct **13** defined within a housing **15** such as a fan case or nacelle, and also drives air along a core flow path C for compression and communication into the combustor section **26** then expansion through the turbine section **28**. A splitter **29** aft of the fan **42** divides the air between the bypass flow path B and the core flow path C. The housing **15** may surround the fan **42** to establish an outer diameter of the bypass duct **13**. The splitter **29** may establish an inner diameter of the bypass duct **13**. Although depicted as a two-spool turbofan gas turbine engine in the disclosed non-limiting embodiment, it should be understood that the concepts described herein are not limited to use with two-spool turbofans as the teachings may be applied to other types of turbine engines including three-spool architectures. The engine **20** may incorporate a variable area nozzle for varying an exit area of the bypass flow path B and/or a thrust reverser for generating reverse thrust.
(11) The exemplary engine **20** generally includes a low speed spool **30** and a high speed spool **32** mounted for rotation about an engine central longitudinal axis A relative to an engine static structure **36** via several bearing systems **38**. It should be understood that various bearing systems **38** at various locations may alternatively or additionally be provided, and the location of bearing systems **38** may be varied as appropriate to the application.
(12) The low speed spool **30** generally includes an inner shaft **40** that interconnects, a first (or low) pressure compressor **44** and a first (or low) pressure turbine **46**. The inner shaft **40** is connected to the fan **42** through a speed change mechanism, which in the exemplary gas turbine engine **20** is illustrated as a geared architecture **48** to drive the fan **42** at a lower speed than the low speed spool **30**. The inner shaft **40** may interconnect the low pressure compressor **44** and low pressure turbine **46** such that the low pressure compressor **44** and low pressure turbine **46** are rotatable at a common speed and in a common direction. In other embodiments, the low pressure turbine **46** drives both the fan **42** and low pressure compressor **44** through the geared architecture **48** such that the fan **42** and low pressure compressor **44** are rotatable at a common speed. Although this application discloses geared architecture **48**, its teaching may benefit direct drive engines having no geared architecture. The high speed spool **32** includes an outer shaft **50** that interconnects a second (or

high) pressure compressor **52** and a second (or high) pressure turbine **54**. A combustor **56** is arranged in the exemplary gas turbine **20** between the high pressure compressor **52** and the high pressure turbine **54**. A mid-turbine frame **57** of the engine static structure **36** may be arranged generally between the high pressure turbine **54** and the low pressure turbine **46**. The mid-turbine frame **57** further supports bearing systems **38** in the turbine section **28**. The inner shaft **40** and the outer shaft **50** are concentric and rotate via bearing systems **38** about the engine central longitudinal axis A which is collinear with their longitudinal axes.
(13) Airflow in the core flow path C is compressed by the low pressure compressor **44** then the high pressure compressor **52**, mixed and burned with fuel in the combustor **56**, then expanded through the high pressure turbine **54** and low pressure turbine **46**. The mid-turbine frame **57** includes airfoils **59** which are in the core flow path C. The turbines **46**, **54** rotationally drive the respective low speed spool **30** and high speed spool **32** in response to the expansion. It will be appreciated that each of the positions of the fan section **22**, compressor section **24**, combustor section **26**, turbine section **28**, and fan drive gear system **48** may be varied. For example, gear system **48** may be located aft of the low pressure compressor, or aft of the combustor section **26** or even aft of turbine section **28**, and fan **42** may be positioned forward or aft of the location of gear system **48**.
(14) The fan **42** may have at least 10 fan blades **43** but no more than 20 or 24 fan blades **43**. In examples, the fan **42** may have between 12 and 18 fan blades **43**, such as 14 fan blades **43**. An exemplary fan size measurement is a maximum radius between the tips of the fan blades **43** and the engine central longitudinal axis A. The maximum radius of the fan blades **43** can be at least 40 inches, or more narrowly no more than 75 inches. For example, the maximum radius of the fan blades **43** can be between 45 inches and 60 inches, such as between 50 inches and 55 inches. Another exemplary fan size measurement is a hub radius, which is defined as distance between a hub of the fan **42** at a location of the leading edges of the fan blades **43** and the engine central longitudinal axis A. The fan blades **43** may establish a fan hub-to-tip ratio, which is defined as a ratio of the hub radius divided by the maximum radius of the fan **42**. The fan hub-to-tip ratio can be less than or equal to 0.35, or more narrowly greater than or equal to 0.20, such as between 0.25 and 0.30. The combination of fan blade counts and fan hub-to-tip ratios disclosed herein can provide the engine **20** with a relatively compact fan arrangement.
(15) The low pressure compressor **44**, high pressure compressor **52**, high pressure turbine **54** and low pressure turbine **46** each include one or more stages having a row of rotatable airfoils. Each stage may include a row of vanes adjacent the rotatable airfoils. The rotatable airfoils are schematically indicated at **47**, and the vanes are schematically indicated at **49**.
(16) The low pressure compressor **44** and low pressure turbine **46** can include an equal number of stages. For example, the engine **20** can include a three-stage low pressure compressor **44**, an eight-stage high pressure compressor **52**, a two-stage high pressure turbine **54**, and a three-stage low pressure turbine **46** to provide a total of sixteen stages. In other examples, the low pressure compressor **44** includes a different (e.g., greater) number of stages than the low pressure turbine **46**. For example, the engine **20** can include a five-stage low pressure compressor **44**, a nine-stage high pressure compressor **52**, a two-stage high pressure turbine **54**, and a four-stage low pressure turbine **46** to provide a total of twenty stages. In other embodiments, the engine **20** includes a four-stage low pressure compressor **44**, a nine-stage high pressure compressor **52**, a two-stage high pressure turbine **54**, and a three-stage low pressure turbine **46** to provide a total of eighteen stages. It should be understood that the engine **20** can incorporate other compressor and turbine stage counts, including any combination of stages disclosed herein.
(17) The engine **20** may be a high-bypass geared aircraft engine. The bypass ratio can be greater than or equal to 10.0 and less than or equal to about 18.0, or more narrowly can be less than or equal to 16.0. The geared architecture **48** may be an epicyclic gear train, such as a planetary gear system or a star gear system. The epicyclic gear train may include a sun gear, a ring gear, a

plurality of intermediate gears meshing with the sun gear and ring gear, and a carrier that supports the intermediate gears. The sun gear may provide an input to the gear train. The ring gear (e.g., star gear system) or carrier (e.g., planetary gear system) may provide an output of the gear train to drive the fan **42**. A gear reduction ratio may be greater than or equal to 2.3, or more narrowly greater than or equal to 3.0, and in some embodiments the gear reduction ratio is greater than or equal to 3.4. The gear reduction ratio may be less than or equal to 4.0. The fan diameter is significantly larger than that of the low pressure compressor **44**. The low pressure turbine **46** can have a pressure ratio that is greater than or equal to 8.0 and in some embodiments is greater than or equal to 10.0. The low pressure turbine pressure ratio can be less than or equal to 13.0, or more narrowly less than or equal to 12.0. Low pressure turbine **46** pressure ratio is pressure measured prior to an inlet of low pressure turbine **46** as related to the pressure at the outlet of the low pressure turbine **46** prior to an exhaust nozzle. It should be understood, however, that the above parameters are only exemplary of one embodiment of a geared architecture engine and that the present invention is applicable to other gas turbine engines including direct drive turbofans. All of these parameters are measured at the cruise condition described below.
(18) A significant amount of thrust is provided by the bypass flow B due to the high bypass ratio. The fan section **22** of the engine **20** is designed for a particular flight condition—typically cruise at about 0.8 Mach and about 35,000 feet (10,668 meters). The flight condition of 0.8 Mach and 35,000 ft (10,668 meters), with the engine at its best fuel consumption—also known as “bucket cruise Thrust Specific Fuel Consumption (‘TSFC’)”—is the industry standard parameter of lbm of fuel being burned divided by lbf of thrust the engine produces at that minimum point. The engine parameters described above, and those in the next paragraph are measured at this condition unless otherwise specified.
(19) “Fan pressure ratio” is the pressure ratio across the fan blade **43** alone, without a Fan Exit Guide Vane (“FEGV”) system. A distance is established in a radial direction between the inner and outer diameters of the bypass duct **13** at an axial position corresponding to a leading edge of the splitter **29** relative to the engine central longitudinal axis A. The fan pressure ratio is a spanwise average of the pressure ratios measured across the fan blade **43** alone over radial positions corresponding to the distance. The fan pressure ratio can be less than or equal to 1.45, or more narrowly greater than or equal to 1.25, such as between 1.30 and 1.40. “Corrected fan tip speed” is the actual fan tip speed in ft/sec divided by an industry standard temperature correction of [(Tram ° R)/(518.7° R)].sup.0.5. The corrected fan tip speed can be less than or equal to 1150.0 ft/second (350.5 meters/second), and can be greater than or equal to 1000.0 ft/second (304.8 meters/second).
(20) The fan **42**, low pressure compressor **44** and high pressure compressor **52** can provide different amounts of compression of the incoming airflow that is delivered downstream to the turbine section **28** and cooperate to establish an overall pressure ratio (OPR). The OPR is a product of the fan pressure ratio across a root (i.e., 0% span) of the fan blade **43** alone, a pressure ratio across the low pressure compressor **44** and a pressure ratio across the high pressure compressor **52**. The pressure ratio of the low pressure compressor **44** is measured as the pressure at the exit of the low pressure compressor **44** divided by the pressure at the inlet of the low pressure compressor **44**. In examples, a sum of the pressure ratio of the low pressure compressor **44** and the fan pressure ratio is between 3.0 and 6.0, or more narrowly is between 4.0 and 5.5. The pressure ratio of the high pressure compressor ratio **52** is measured as the pressure at the exit of the high pressure compressor **52** divided by the pressure at the inlet of the high pressure compressor **52**. In examples, the pressure ratio of the high pressure compressor **52** is between 9.0 and 12.0, or more narrowly is between 10.0 and 11.5. The OPR can be equal to or greater than 45.0, and can be less than or equal to 70.0, such as between 50.0 and 60.0. The overall and compressor pressure ratios disclosed herein are measured at the cruise condition described above, and can be utilized in two-spool architectures such as the engine **20** as well as three-spool engine architectures.
(21) The engine **20** establishes a turbine entry temperature (TET). The TET is defined as a

maximum temperature of combustion products communicated to an inlet of the turbine section **28** at a maximum takeoff (MTO) condition. The inlet is established at the leading edges of the axially forwardmost row of airfoils of the turbine section **28**, and MTO is measured at maximum thrust of the engine **20** at static sea-level and 86 degrees Fahrenheit (° F.). The TET may be greater than or equal to 2700.0° F., or more narrowly less than or equal to 3500.0° F., such as between 2750.0° F. and 3350.0° F. The relatively high TET can be utilized in combination with the other techniques disclosed herein to provide a compact turbine arrangement.
(22) The engine **20** establishes an exhaust gas temperature (EGT). The EGT is defined as a maximum temperature of combustion products in the core flow path C communicated to at the trailing edges of the axially aftmost row of airfoils of the turbine section **28** at the MTO condition. The EGT may be less than or equal to 1000.0° F., or more narrowly greater than or equal to 800.0° F., such as between 900.0° F. and 975.0° F. The relatively low EGT can be utilized in combination with the other techniques disclosed herein to reduce fuel consumption.
(23) The engine **20** may operate in environmentally degraded conditions, such as sand storms, soot clouds, etc. The engine **20** may ingest foreign debris or particulates during operation. These may include calcium, magnesium, aluminum, and silicon (CMAS) particulates in the form of volcanic ash, sand, dust, salt, etc. The particulates may be deposited on surfaces of various gas turbine components of the engine **20** (see, e.g., particulates P of FIG. **3**). The engine **20** may operate at elevated temperatures. With elevated temperatures, the particulates may form a glass coating which may bond to, or otherwise accumulate on, surfaces of the components. The accretion of glass on the components may cause instability and reduce performance. The glass and/or other debris may substantially block or otherwise inhibit flow through cooling passages in the components. This may result in reduced cooling augmentation, which may decrease life of the component.
(24) Referring to FIG. **2**, with continuing reference to FIG. **1**, an accretion detection system **60** for a gas turbine engine is disclosed. The detection system **60** may be utilized to detect the accretion of glass and other debris on one or more of gas turbine engine components **64**, including rotatable and/or static components of the engine **20**. The system **60** may be utilized to provide prognostics and/or diagnostics associated with performance and maintenance of the engine **20**. The components **64** may include rotatable and/or static components, such as one or more rotatable airfoils, hubs, ducts, etc. The components **64** may include any components of a gas turbine engine that may be exposed to environment debris, including any of the components of the engine **20**. The system **60** may include a controller **61** operable to determine accretion of glass and/or other debris on one or more of the components **64**. The controller **61** may include processor(s) and memory. In implementations, the controller **61** may be a full-authority digital electronic control (FADEC), an electronic engine control (EEC) and/or a separate controller. One would understand how to program and/or otherwise configure the controller **61** with logic to implement any of the teachings disclosed herein.
(25) The system **60** may include one or more sensors **62** distributed throughout the engine **20** and/or associated aircraft. The sensors **62** may be configured to measure one or more conditions of the engine **20**, including any of the conditions disclosed herein such as temperature, pressure, etc., associated with one or more of the components **64**. The sensors **62** may be adjacent to, disposed along, and/or at least partially incorporated in one or more of the components **64**. In implementations, one or more of the sensors **62** may be a vibration sensor operable to detect vibration of one or more adjacent components **64**. Various vibration sensors may be utilized, including cameras, lasers and strain gauges. The controller **61** may be operatively coupled to the sensors **62**, including wireless and/or wired connections.
(26) In the implementation of FIG. **3**, one or more sensors **62** may be incorporated in a propulsor section **22**. The propulsor section **22** may include a propulsor **42** for generating thrust. A turbine may drive the propulsor **42**, such as the turbine **46** (FIG. **1**). Although the disclosure primarily refers to the propulsor section **22**, it should be understood that other portions of the engine **20** may

benefit from the teachings disclosed herein, including ducts and airfoils in the compressor section **24** and/or turbine section **28**, combustor panels or liners in the combustor section **26**, and other portions of the engine **20** that may be subject to elevated temperature conditions during engine operation. Other systems may benefit from the teachings disclosed herein, including gas turbine engines lacking a propulsor.

(27) The section **22** may include one or more rotatable airfoils **66** distributed about a rotatable hub **68**. The airfoils **66** may be rotatable about the engine axis A. The airfoils **66** may be propulsor blades for generating thrust, which in implementations may be fan blades **42** (FIG. **1**).

(28) One or more of the vibration sensors **62** may be operable to detect vibration of at least one or more of the airfoils **66**, including at one or more rotational frequencies. The rotational frequency may be measured relative to an axis of rotation, such as the engine axis A. The rotational frequencies may be associated with rotation of the airfoils **66** at different rotational speeds about the engine axis A during operation of the engine **20**. The vibration sensor **62** may be operable to detect vibration for rotational frequencies across any and all operating conditions of the engine **20** and/or associated aircraft, including ground idle, taxiing, maximum take-off, cruise and approach. The vibration sensor **62** may be operable to generate signal(s) associated with vibration of one or more of the airfoils **66** at one or more rotational frequencies.

(29) Referring back to FIG. **2**, with continuing reference to FIG. **3**, the controller **61** may include an interface module **70**, comparison module **72** and/or calibration module **73**, which may be operable to communicate with each other. Although three modules are disclosed, it should be understood that the functionality of the controller **61** may be combined into a single module or may be implemented by two or more modules. The interface module **70** may be operable to communicate with one or more subsystems and/or sensors **62** to access various data and other information relating to operation of the engine **20**, including one or more conditions of the component(s) **64** such as pressure, temperature, vibration, rotational speed, etc. The rotational speed may be measured in revolutions per minute (RPM). The interface module **70** may be operable to communicate with one or more subsystems of the engine and/or associated aircraft to obtain various conditions of the aircraft, such as velocity, altitude, etc. of the aircraft. The interface module **70** may be operable to communicate with one or more external systems (e.g., NASA) to obtain weather data and/or other information relating to the environmental conditions associated with the planned and/or actual flight path of the aircraft, such as dust patterns across the globe.

(30) The comparison module **72** may be operable to detect or otherwise determine an accretion level associated with accretion of glass and/or other debris on the component(s) **64**, such as one or more of the airfoils **66**. The accretion level may be associated with a presence and/or an amount of glass and/or other debris on the component(s) **64**, which may accumulate during flight.

(31) Various techniques may be utilized to perform the determination. In implementations, the comparison module **72** may be operable to determine the accretion level in response to comparing vibration of the airfoil(s) **66** at one or more rotational frequencies of the respective the airfoil(s) **66** to one or more respective vibration thresholds. Each vibration threshold may be associated with a respective one of the rotational frequencies and/or range of rotational frequencies. The vibration threshold may be associated with an amplitude and/or other characteristic of the vibration.

(32) One or more (e.g., predetermined) vibratory patterns **74** may be established for each of the components **64**, including the airfoils **66**. The vibratory pattern **74** may be associated with a single component **64**. A common vibratory pattern **74** may be established for a set of components **64**, such as an array of the airfoils **66**. Vibration of each component **64** of the set of components **64** may be compared to the common vibratory pattern **74**. The vibratory pattern **74** may be established prior to and/or during operation of the engine **20**. The vibratory pattern **74** may be established based on the specific component **64** incorporated into the engine **20** and/or a representative component associated with the specific component **64**. The representative component may be a prototype, a component from the same lot, a parametric model, etc. The rotational frequencies and respective

vibration thresholds may be associated with the respective vibratory pattern **74**.
(33) The comparison module **72** may be operable to determine an accretion condition associated with accretion of glass and/or other debris on the respective airfoil(s) **66** in response to comparing signal(s) from the vibration sensor(s) **62** to the respective vibratory pattern **74**. The comparison module **72** may be operable to determine the accretion condition in response to comparing an amplitude associated with the signal(s) generated by the vibration sensor(s) **62** to the vibration threshold associated with the respective rotational frequency.
(34) The vibration sensor(s) **62** may be positioned a distance from the airfoils **66**. In implementations, the vibration sensors **62** may be time-of-arrival sensors operable to determine passing of a component such as the rotatable airfoils **66** through a detection field (e.g., line of sight) of the respective sensor **62**. The comparison module **72** may be operable to determine a blade passing frequency in response to signal(s) from the vibration sensor(s) **62** associated with passing of the one or more airfoils **66** through the detection field. The blade passing frequency may be calculated as a product of a rotational speed and total number of airfoils **72** in an array. The comparison module **72** may be operable to calculate a deviation based upon a comparison of an expected time of arrival and an actual time of arrival of an edge or other feature of the airfoil **66**. The amplitude of the vibration may be associated with a difference between the expected time of arrival and actual time of arrival of the airfoil **66**. The comparison module **72** may be operable to filter and/or average two or more amplitudes from a set of the blade passing frequency information. The filtered and/or averaged amplitudes may compared to the vibration threshold(s).
(35) The calibration module **73** may be operable to perform a calibration sequence in which a baseline is established for one or more of the components **64**. The calibration module **73** may perform the calibration sequence prior to, during and/or subsequent to flight. The baseline may be associated with vibration of the respective component **64** when surfaces of the component **64** are substantially free of any environmental debris (e.g., particulates of less than 1 micron in size). The baseline may be associated with vibration at the respective rotational frequencies of the vibratory pattern **74**. The calibration module **73** may be operable to adjust or otherwise set the vibration threshold(s) based on vibration associated with the baseline.
(36) The rotational frequencies of the component **64** may be selected based on observing the vibratory response(s) of the component **64** during engine operation. The component **64** may exhibit different vibratory responses across different rotational frequencies. In implementations, the vibratory pattern **74** may be associated with two or more rotational frequencies of the respective component **64**. The vibratory pattern **74** may be associated with two or more vibration thresholds. Each of the vibration thresholds may be associated with the respective rotational frequencies. Vibration may be associated with an amplitude at each of the respective rotational frequencies. In the implementation of FIG. **5**C, a set of vibration thresholds T**1** to T**4** associated with respective rotational frequencies is disclosed.
(37) Various techniques may be utilized to establish the vibration thresholds. In implementations, the vibration thresholds may be assigned independently of the other vibration thresholds associated with the same vibratory pattern **74**. In other implementations, one or more of the vibration thresholds may be assigned relative to one or more other vibration thresholds associated with the same vibratory pattern **74**. The vibration thresholds may include a first vibration threshold and a second vibration threshold. The first vibration threshold may be associated with a first rotational frequency of the component **64**. The second vibration threshold may be associated with a second rotational frequency of the component **64**. The first vibration threshold may be assigned a value or percentage that is above or below the second vibration threshold (e.g., ±10 percent).
(38) The comparison module **72** may be operable to determine the accretion level in response to comparing at least one amplitude associated with vibration of the airfoil **66** and/or component **64** at the respective rotational frequency to the respective vibration threshold associated with the vibratory pattern **74**. The comparison module **72** may be operable to determine the accretion level

in response to determining that the amplitude(s) of vibration meet one or more, or all of, the respective vibration threshold(s) associated with the vibration patter **74**.
(39) The vibratory pattern **74** may be established based on different amounts of accretion of glass and/or other debris and associated vibration for each of the amounts of accretion at the rotational frequencies. FIGS. **4**A-**4**C disclose plots associated with accretion of glass on a static or rotatable component, such as a rotatable blade. The plots disclose amplitudes of vibration with respect to a set of distinct rotational frequencies (e.g., frequencies F.sub.A to F.sub.D). The frequencies may be measured in hertz (Hz). FIG. **4**A may be associated with a baseline response in which substantially no glass and/or other debris is disposed on the component. FIG. **4**B may be associated with an amount of glass and/or other debris disposed on the component, such as approximately 1 micron in size. FIG. **4**C may be associated with a different (e.g., lesser or greater) amount of glass and/or other debris disposed on the component. The amplitudes are associated with a vibratory response of the component at the respective rotational frequencies. The set of amplitudes may be utilized to establish a vibratory pattern **74** for the respective component. The vibratory pattern **74** may exclude one or more frequencies and/or ranges of frequencies between the rotational frequencies that define the vibratory pattern **74**. In implementations, the rotational frequencies associated with the vibratory pattern **74** may be associated with respective operating conditions of the engine **20**, such as different rotational speeds of the spools **30**, **32** (e.g., idle and redline speeds), and/or operating conditions of the associated aircraft such as ground idle, maximum take-off, cruise, approach and/or landing.
(40) The comparison module **72** may be operable to cause one or more indicators **76** to be generated based on the detected accretion of glass and/or other debris on the component(s) **64**. The indicators **76** may include a visual or audible warning to the cockpit or crew. The indicators **76** may include one or more flags or maintenance indicators to alert maintenance crews that one or more specified components **64** of the engine **20** are associated with an accretion condition. The maintenance indicators may require clearing by maintenance personnel once the maintenance indicators have been set. The comparison module **72** may be operable to cause one or more indicator **76** to be generated in response to determining the accretion of glass and/or other debris on the component(s) **64**. The comparison module **72** may be operable to cause one or more indicator **76** to be generated in response to determining that the accretion level meets an (e.g., predetermined) accretion threshold. The accretion threshold may be the presence of glass and/or other debris. In implementations, the accretion threshold may be a predetermined mass and/or thickness the debris on the surfaces of the component **64** (e.g., 1 micron or more), which may be associated with reduced performance.
(41) The comparison module **72** may be operable to determine a brittleness characteristic (e.g., factor) associated with accretion of glass based on the accretion level. The brittleness factor may be calculated according to the Brinell hardness factor. The brittleness may be determined based on the amount of accretion. FIG. **5** discloses a plot associated with brittleness according to an implementation. The comparison module **72** may be operable to obtain information from one or more of the sensors **62** and/or aircraft systems relating to operating conditions within the engine **20** and/or environmental conditions of an associated aircraft. The conditions may include dust ingestion, temperature, and/or pressure. The comparison module **72** may be operable to compare the measured condition(s) to a parametric model or relationship to determine the brittleness characteristic of the accumulated glass. The determined brittleness may be utilized to indicate a removal technique. The determined brittleness may be compared to a total time on wing and/or time since the last maintenance cycle of the engine **20**, which may be utilized to set and/or adjust any of the thresholds and/or durations disclosed herein.
(42) The controller **61** may be operable to cause a change in operation of the engine **20** in response to determining the accretion of glass and/or other debris on the component(s) **64**. The comparison module **72** may be operable to cause excitation of the component(s) **64**, such as one or more of the

airfoils **66**, to remove or otherwise release the glass and/or other debris. The comparison module **72** may be operable to cause the excitation in response to determining the occurrence of an accretion condition. The comparison module **72** may be operable to cause the excitation to remove or otherwise release the glass and/or other debris associated with a determined accretion (e.g., amount) level in response to determining that the accretion level meets an accretion threshold. In implementations, the vibratory pattern **74** may include a set of vibratory responses associated with different amounts of accretion utilized to establish the baseline. The comparison module **72** may determine the present amount of accretion in response to comparing the measured vibration at the rotational frequencies to the set of vibratory responses of the vibratory pattern **74** to determine a "best fit" associated with predetermined amounts of accretion (e.g., the plots of FIGS. **4**A-**4**C). For example, each of the plots of FIGS. **4**A-**4**C may be associated with a respective vibratory response based on different amounts of accretion. The vibratory pattern **74** may be associated with the set of vibratory responses, which represent different amounts of accretion (or lack thereof). The best fit may be determined by comparing a summation of the (e.g., absolute) differences between the measured and predetermined amplitudes for the set of the rotational frequencies and assigning the accretion level associated with the vibratory response of the vibratory pattern **74** that has the least total difference (e.g., accretion level associated with one of the plots of FIGS. **4**A-**4**C). The set of vibratory responses may be a set of datasets associated with different amounts of accretion and respective amplitudes, which may include and/or differ from the baseline vibratory response.

(43) Various techniques may be utilized to excite the components **64**. In implementations, the comparison module **72** may be operable to cause excitation of the airfoil(s) **66** and/or other component(s) **64** to release the glass and/or other debris in response to causing a change in rotational speed of the component(s) **64** such that the rotational frequency approaches a resonant frequency of the respective component(s) **64**, which may cause a substantially instantaneous surge or response. The resonant frequency may differ from the baseline vibratory response of the component **64**. The component **64** may flutter or otherwise vibrate at the resonant frequency for a sufficient duration to remove or otherwise release the glass and/or other debris. The comparison module **72** may be operable to cause the component **64** to rotate at approximately the resonant frequency for a predetermined duration. The comparison module **72** may be operable to block requests to change the rotational speed during the predetermined duration, but the comparison module **72** may be operable to permit requests to change the rotational speed prior and/or subsequent to the predetermined duration.

(44) The comparison module **72** may be coupled to one or more actuators **78**. The actuators **78** may be adjacent to, disposed on, and/or incorporated into the components **64** (e.g., FIG. **3**). Various actuators **78** may be utilized, such as a piezo-electric component responsive to an electrical signal. The comparison module **72** may be operable to cause excitation of the airfoil(s) **66** and/or other component(s) **64** to remove or otherwise release the glass and/or other debris in response to actuating one or more of the respective actuators **78**.

(45) FIG. **6** discloses a method of operation in a flowchart **90**. The method **90** may be utilized in operation of a gas turbine engine, such as the engine **20**. Fewer or additional steps than are recited below could be performed within the scope of this disclosure, and the recited order of steps is not intended to limit this disclosure. The controller **61** and any of the modules **70**, **72**, **73** may be programmed with logic for performing method **90**. Reference is made to the engine **20** and detection system **60**.

(46) At step **90**A, one or more vibratory patterns **74** may be established for one or more gas turbine engine components **64**, such as airfoils **66**. The vibratory pattern **74** may be associated with a vibratory response of the component **64** to glass and/or other debris on surfaces of the component **64**. The vibratory pattern **74** may be established utilizing any of the techniques disclosed herein. The vibratory pattern **74** may be predetermined prior to operation of the engine **20**. The vibratory pattern **74** may be established based on accretion of glass and/or other debris at one or more

rotational frequencies of the component **64**. Step **90**A may include establishing the vibratory pattern **74** based on the specific component **64** incorporated into the engine **20** and/or a representative component associated with the specific component **64**. Establishing the vibratory pattern **74** may include establishing one or more vibration thresholds associated with accretion of glass and/or other debris at the respective rotational frequencies.

(47) At step **90**B, a model incorporating the vibratory pattern(s) **74** may be calibrated. The calibration module **73** and/or another portion of the system **60** may incorporate the model. Calibrating the model may include determining a vibratory response of the component **64** during a baseline condition in which substantially no glass and/or other debris is disposed on the component **64**. The baseline vibratory response of the component **64** may be determined at the one or more, or all, rotational frequencies associated with the vibratory pattern **74**. Calibrating the model may include adjusting one or more vibratory thresholds associated with the vibratory pattern **74** based on the baseline vibratory response of the component **64**. Calibrating the model may improve accuracy in determining accretion of glass and/or other debris on the component **64**. In other implementations, step **90**B may be omitted.

(48) At step **90**C, vibration of the component(s) **64** may be determined, such as the airfoil(s) **66**. Step **90**C may include determining vibration of the component **64** at one or more, or all, rotational frequencies associated with the vibratory pattern **74** during engine operation. The rotational frequencies may be associated with minimum, intermediate and/or maximum rotational speeds of the component **64**. The rotational frequencies may be associated with any of the engine and/or aircraft conditions disclosed herein. Step **90**C may include determining one or more amplitudes associated with the vibration at the rotational frequencies.

(49) At step **90**D, the vibration may be compared to the vibratory pattern **74** of the respective component **64**. Various techniques may be utilized to determine the vibration, including any of the techniques disclosed herein.

(50) At step **90**E, an accretion condition may be determined based on the comparison at step **90**D. The accretion condition may be associated with a determination that glass and/or other debris is disposed on surfaces of the component **64**, which may exhibit a vibratory response associated with the vibratory pattern **74**. Step **90**E may include determining an accretion of glass and/or other debris on the component **64** in response to comparing the determined vibration to the vibratory pattern **74**, which may include comparing the vibration to one or more vibration thresholds associated with the respective rotational frequencies of the vibratory pattern **74**. Determining the accretion of glass and/or other debris may include determining that the measured amplitude(s) associated with the vibration meet the respective vibration threshold(s). In implementations, the vibration threshold may be met when the amplitude is equal to or greater than the vibration threshold. In other implementations, the vibration threshold may be met when the amplitude is less than or equal to the vibration threshold.

(51) At step **90**F, a brittleness of the detected glass and/or other debris may be determined. The brittleness may be determined utilizing any of the techniques disclosed herein. The determined brittleness may be utilized to set and/or adjust any of the threshold(s) disclosed herein, the duration for exciting the component **64**, and/or criterion for generating the indicator(s) **76**.

(52) At step **90**G, one or more indicators **76** may be generated. Step **90**F may include generating the indicator(s) **76** in response to determining the accretion of glass and/or other debris associated with the vibration. The indicators **76** may be utilized according to any of the teachings disclosed herein. In implementations, maintenance crew may wash or otherwise clean the component(s) **64** and/or engine **20** in response to the indicator(s) **76**.

(53) At step **90**H, the method may cause a change in one or more conditions of the component(s) **64**, including during operation of the engine **20** in maintenance and/or in flight. Step **90**H may include exciting the airfoil **66** or other component **64** to release at least a portion of the glass and/or other debris from the component **64** in response to determining the accretion. Various techniques

may be utilized to excite the component **64**, including any of the techniques disclosed herein. In implementations, step **90**H may include changing a rotational speed of the airfoil **66** or other component **64** such that the rotational speed is substantially equal to or otherwise approaches a (e.g., predetermined) resonant frequency of the component **64**. The component **64** may vibrate at approximately the resonant frequency for a predetermined duration, or otherwise for a sufficient time, to remove or otherwise release the glass and/or other debris. The terms “approximately,” “about” and “substantially” mean±10 percent of the stated value or relationship unless otherwise indicated. Step **90**H may include blocking requests to change the rotational speed during the predetermined duration, but may include permitting requests to change the rotational speed prior and/or subsequent to the predetermined duration. Step **90**C to **90**E may be repeated to validate that the component **64** is operating at substantially the baseline and/or calibrated vibratory response.
(54) The systems and methods disclosed herein may be utilized to determine the accretion of glass and/or other debris on surfaces of various components of a gas turbine engine. The determination may be made during maintenance and/or in flight. The glass and/or other debris may be removed or otherwise released from the surfaces utilizing any of the techniques disclosed herein. The disclosed techniques may reduce external intervention that may otherwise be necessary to clean the surfaces to meet operational standards. Removing the debris may improve engine performance and time on wing.
(55) It should be understood that relative positional terms such as “forward,” “aft,” “upper,” “lower,” “above,” “below,” and the like are with reference to the normal operational altitude of the engine and should not be considered otherwise limiting.
(56) Although the different examples have the specific components shown in the illustrations, embodiments of this disclosure are not limited to those particular combinations. It is possible to use some of the components or features from one of the examples in combination with features or components from another one of the examples.
(57) Although particular step sequences are shown, described, and claimed, it should be understood that steps may be performed in any order, separated or combined unless otherwise indicated and will still benefit from the present disclosure.
(58) The foregoing description is exemplary rather than defined by the limitations within. Various non-limiting embodiments are disclosed herein, however, one of ordinary skill in the art would recognize that various modifications and variations in light of the above teachings will fall within the scope of the appended claims. It is therefore to be understood that within the scope of the appended claims, the disclosure may be practiced other than as specifically described. For that reason the appended claims should be studied to determine true scope and content.

Claims

1. An assembly for a gas turbine engine comprising: at least one rotatable airfoil; at least one vibration sensor operable to detect vibration of the at least one rotatable airfoil at one or more rotational frequencies; and a controller operatively coupled to the at least one vibration sensor, wherein the controller is configured to determine an accretion level associated with accretion of glass on the at least one rotatable airfoil in response to comparing vibration of the at least one rotatable airfoil at the one or more rotational frequencies to a vibratory pattern associated with accretion of glass, wherein the vibratory pattern is associated with the one or more rotational frequencies and one or more respective vibration thresholds, wherein the controller is configured to determine the accretion level in response to comparing at least one amplitude associated with vibration of the at least one rotatable airfoil at the respective rotational frequency to the respective vibration threshold; and wherein the vibratory pattern is established based on different amounts of accretion of glass and associated vibration for each of the amounts of accretion of glass at the one or more rotational frequencies.

2. The assembly as recited in claim 1, wherein the controller is configured to cause an indicator to be generated in response to determining that the accretion level meets an accretion threshold.
3. The assembly as recited in claim 1, wherein the controller is configured to cause excitation of the at least one rotatable airfoil to release debris associated with the accretion level in response to determining that the accretion level meets an accretion threshold.
4. The assembly as recited in claim 3, wherein the controller is configured to cause excitation of the at least one rotatable airfoil by causing a rotational speed of the at least one rotatable airfoil to approach a resonant frequency of the at least one rotatable airfoil.
5. The assembly as recited in claim 1, wherein the one or more rotational frequencies includes a plurality of rotational frequencies associated with the vibratory pattern, the one or more vibration thresholds includes a plurality of vibration thresholds associated with the respective rotational frequencies, the at least one amplitude includes a plurality of amplitudes associated with the respective rotational frequencies, and the controller is configured to determine the accretion level in response to determining that the respective amplitudes meet the respective vibration thresholds.
6. The assembly as recited in claim 1, wherein the controller is configured to determine the accretion level in response to determining a best fit of vibration at the one or more rotational frequencies to a set of vibratory responses associated with the vibratory pattern and respective amounts of accretion.
7. The assembly as recited in claim 1, wherein: the at least one rotatable airfoil is a propulsor blade for generating thrust.
8. A gas turbine engine comprising: a propulsor section including a propulsor; a compressor; a turbine that drives the propulsor; a plurality of airfoils rotatable about an engine axis; at least one vibration sensor operable to detect vibration and configured to generate a signal associated with detected vibration of one or more airfoils of the plurality of airfoils at one or more rotational frequencies; and a controller operatively coupled to the at least one vibration sensor, wherein the controller is configured to determine an accretion level associated with accretion of glass on the one or more airfoils in response to comparing the signal to a vibratory pattern associated with accretion of glass, wherein the vibratory pattern is associated with the one or more rotational frequencies and one or more respective vibration thresholds, wherein the controller is configured to determine the accretion level in response to comparing at least one amplitude of the signal associated with vibration of the one or more airfoils at the respective rotational frequency to the respective vibration threshold; and wherein the vibratory pattern is established based on different amounts of accretion of glass and associated vibration for each of the amounts of accretion of glass at the one or more rotational frequencies.
9. The gas turbine engine as recited in claim 8, wherein: the one or more rotational frequencies include a plurality of rotational frequencies associated with rotation of the plurality of airfoils about an engine axis of the gas turbine engine; the vibratory pattern is associated with the plurality of rotational frequencies and a plurality of respective vibration thresholds; and the controller is configured to determine the accretion level in response to comparing respective amplitudes of a plurality of amplitudes of the signal respectively associated with the plurality of rotational frequencies to the respective vibration threshold associated with the respective rotational frequency.
10. The gas turbine engine as recited in claim 8, wherein the controller is configured to cause excitation of one or more of the plurality of airfoils to remove glass on the one or more airfoils in response to determining the accretion level.
11. The gas turbine engine as recited in claim 8, wherein the controller is configured to cause a change in a rotational speed of the plurality of airfoils such that the rotational speed approaches a resonant frequency of the plurality of airfoils.