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SYSTEM AND METHOD FOR DETECTING A PERFORMANCE DEGRADATION OF A BLEED-OFF VALVE

Abstract

Systems and methods for detecting a performance degradation of a pneumatic bleed-off valve installed in a compressor section of a gas turbine engine are provided. A method includes acquiring a first relationship between a pressure ratio across a compressor of the engine and a rotational speed of a spool of the engine during an acceleration of the spool, and acquiring a second relationship between the pressure ratio across the compressor and the rotational speed of the spool during the deceleration of the spool. A cross-over rotational speed corresponding to an intersection of the first relationship and the second relationship is determined. The performance degradation of the pneumatic bleed-off valve is detected when the cross-over rotational speed is outside a prescribed range.

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Background/Summary

TECHNICAL FIELD

[0001] The disclosure relates generally to gas turbine engines, and more particularly to detecting a performance degradation of a bleed-off valve installed in a gas turbine engine.

BACKGROUND

[0002] A gas turbine engine used for aircraft propulsion may include a bleed-off valve to regulate air pressure in a compressor section of the gas turbine engine. Proper operation of the bleed-off valve promotes an efficient operation of the gas turbine engine and also protects the gas turbine engine from aerodynamic instabilities such as compressor stall or surge. Improvement in detecting a performance degradation of a bleed-off valve is desirable.

SUMMARY

[0003] In one aspect, the disclosure describes a method for detecting a performance degradation of a pneumatic bleed-off valve installed in a compressor section of a gas turbine engine, the method comprising: operating the gas turbine engine to cause an acceleration of a spool of the gas turbine engine from a first rotational speed to a second rotational speed, the spool including a compressor of the gas turbine engine; during the acceleration of the spool, acquiring a first relationship between a pressure ratio across the compressor and a rotational speed of the spool; operating the gas turbine engine to cause a deceleration of the spool from the second rotational speed to the first rotational speed; during the deceleration of the spool, acquiring a second relationship between the pressure ratio across the compressor and the rotational speed of the spool; determining a cross-over rotational speed corresponding to an intersection of the first relationship and the second relationship, the cross-over rotational speed being between the first rotational speed and the second rotational speed; and detecting the performance degradation of the pneumatic bleed-off valve when the cross-over rotational speed is lower than a rotational speed threshold.

[0004] In another aspect, the disclosure describes a method for detecting a slow modulation time of a pneumatically-actuated bleed-off valve without positional feedback from the bleed-off valve, the bleed-off valve being installed at an intermediate stage of a compressor section of a gas turbine engine, the method comprising: operating the gas turbine engine to cause an acceleration of a spool of the gas turbine engine from a first rotational speed to a second rotational speed, the spool including a compressor of the gas turbine engine; during the acceleration of the spool: causing the bleed-off valve to transition from an open position to a closed position; and acquiring a first relationship between a pressure ratio across the compressor and a rotational speed of the spool; operating the gas turbine engine to cause a deceleration of the spool from the second rotational speed to the first rotational speed; during the deceleration of the spool: causing the bleed-off valve to transition from the closed position to the open position; and acquiring a second relationship between the pressure ratio across the compressor and the rotational speed of the spool; determining a cross-over rotational speed corresponding to an intersection of the first relationship and the second relationship, the cross-over rotational speed being between the first rotational speed and the second rotational speed; and detecting the slow modulation time of the bleed-off valve when the cross-over rotational speed is lower than a rotational speed threshold.

[0005] In a further aspect, the disclosure describes a system for detecting a performance degradation of a pneumatic bleed-off valve installed in a compressor section of a gas turbine engine, the system comprising: sensors configured to acquire: a rotational speed of a spool of the gas turbine engine, the spool including a compressor of the gas turbine engine; and a pressure ratio across the compressor; one or more data processors; and non-transitory machine-readable memory storing: a first relationship between a pressure ratio across the compressor and the rotational speed of the spool acquired during an acceleration of the spool using the sensors; a second relationship

between the pressure ratio across the compressor and the rotational speed of the spool acquired during a deceleration of the spool using the sensors; and instructions executable by the one or more data processors and configured to cause the one or more data processors to: determine a cross-over rotational speed corresponding to an intersection of the first relationship and the second relationship; and detect the performance degradation of the pneumatic bleed-off valve when the cross-over rotational speed is lower than a rotational speed threshold.
[0006] 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
[0007] Reference is now made to the accompanying drawings, in which:
[0008] FIG. **1** shows an axial cross-section view of a turboprop gas turbine engine including a bleed-off valve, and a schematic representation of a system for detecting a performance degradation of the bleed-off valve;
[0009] FIGS. **2**A and **2**B show an axial cross-section view of an exemplary pneumatic bleed-off valve in a closed state and in an open state respectively;
[0010] FIG. **3** is another schematic representation of the system for detecting the performance degradation of the bleed-off valve;
[0011] FIG. **4** is a flow diagram of an exemplary method for detecting the performance degradation of the bleed-off valve;
[0012] FIG. **5** is a plot showing baseline first and second relationships between a pressure ratio across the compressor of the gas turbine engine and a rotational speed of a spool including the compressor during an acceleration and a deceleration of the spool;
[0013] FIG. **6** is a plot showing actual first and second relationships between the pressure ratio across the compressor of the gas turbine engine and the rotational speed of the spool during the acceleration and the deceleration of the spool in relation to the baseline first and second relationships of FIG. **5**;
[0014] FIG. **7** is a flow diagram of another exemplary method for detecting the performance degradation of the bleed-off valve; and
[0015] FIG. **8** is a flow diagram of another exemplary method for detecting the performance degradation of the bleed-off valve.
DETAILED DESCRIPTION
[0016] The present disclosure describes systems and methods for detecting a performance degradation of a pneumatically-actuated bleed-off valve that is installed in a gas turbine engine. In some embodiments, the systems and methods described herein may promote a relatively early detection of the performance degradation of the bleed-off valve to reduce a likelihood of an undesirable aerodynamic instability inside of the engine. In some embodiments, the systems and methods described herein may facilitate an in-situ (e.g., on-wing, during flight) evaluation of the pneumatic bleed-off valve by monitoring one or more characteristics of the compressor during an acceleration and deceleration of the compressor and the engine. In the event that a degradation of performance is detected, a suitable alert may be generate to signal that a maintenance action is required. Aspects of various embodiments are described through reference to the drawings.
[0017] The term “connected” may include both direct connection (in which two elements that are connected to each other contact each other) and indirect connection (in which at least one additional element is located between the two elements). 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. As used herein, the singular forms

"a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise.

[0018] FIG. **1** shows a schematic axial cross-section view of an exemplary reverse flow turboprop gas turbine engine **10** (referred hereinafter as "engine **10**") including one or more pneumatic bleed-off valves **12** (referred hereinafter in the singular as "BOV **12**"), and a schematic representation of system **13** for detecting a performance degradation of BOV **12**. Even though the following description and accompanying drawings specifically refer to a turboprop gas turbine engine as an example, aspects of the present disclosure may be equally applicable to other types of gas turbine engines including turboshaft engines, turbofan engines, turbojet engines, industrial gas turbine engines, and auxiliary power units. Engine **10** may be mounted to an aircraft for propelling the aircraft. Engine **10** may be of a type preferably provided for use in subsonic flight to drive a load such as propeller **14** (or other air mover) via low-pressure shaft **16** (sometimes called "power shaft") coupled to low-pressure turbine **18**. Low-pressure turbine **18** and low-pressure shaft **16** may be part of a first spool of engine **10** known as a low-pressure spool. Engine **10** may include a second or high-pressure spool including high-pressure turbine **20**, (e.g., multistage) compressor **22** and high-pressure shaft **24**.

[0019] Compressor **22** may draw ambient air into engine **10** via annular radial air inlet duct **26**, increase the pressure of the drawn air and deliver the pressurized air to combustor **28** where the pressurized air is mixed with fuel and ignited for generating an annular stream of hot combustion gas. High-pressure turbine **20** may extract energy from the hot expanding combustion gas and thereby drive compressor **22**. The hot combustion gas leaving high-pressure turbine **20** may be accelerated as it further expands, flows through and drives low-pressure turbine **18**, which in turn drives propeller **14**. The combustion gas may then exit engine **10** via exhaust duct **30**.

[0020] System **13** may include a plurality of sensors for acquiring different operating parameters of engine **10**. For example, system **13** may include one or more shaft speed sensor(s) **32** (referred hereinafter in the singular) for acquiring a rotational speed N of the high-pressure spool which includes at least part of compressor **22**. In some embodiments, speed sensor **32** may include a Hall effect sensor or a magnetoresistive sensor for example. System **13** may include one or more pressure sensors **34**, **36** that may be used to acquire a pressure ratio (PR) across part of compressor **22** and/or across an entirety of compressor **22**. In some embodiments, PR may be acquired using individual pressure sensors **34**, **36** disposed at different locations along gas path **46** including compressor **22**. First pressure sensor **34** may be disposed at or near an inlet of compressor **22** and may be used to acquire first pressure Pa of the air received in compressor **22**. Second pressure sensor **36** may be disposed at or near an outlet of the compressor **22** and may be used to acquire second pressure Pb of the air discharged from compressor **22** and upstream of combustor **28**. In various embodiments, pressure sensors **34**, **36** may be of a strain gauge type, of a piezoelectric type, of a capacitive type or of another suitable type of pressure sensor for example.

[0021] Pressure sensors **34**, **36** may be located as shown in FIG. **1** in order to determine an overall PR of compressor **22** across an entirety of compressor **22**. Alternatively, in some embodiments, first pressure sensor **34** and/or second pressure sensor **36** may be disposed at an intermediate stage of compressor **22** so that the PR may be a partial PR across only a part of compressor **22** less than an entirety of compressor **22**.

[0022] System **13** may include one or more ambient condition sensors **40**, which may be configured to acquire one or more sensed parameters indicative of ambient condition **42** in which engine **10** is currently operating. Such sensed parameters may include an outside temperature, an altitude of an aircraft being propelled by engine **10**, an airspeed of the aircraft and/or any other parameter(s) determined to influence the operation of BOV **12** during the methods described herein.

[0023] Speed sensor **32**, pressure sensors **34**, **36** and optionally ambient condition sensor(s) **40** may be operatively connected to computer **38** so that shaft speed N, first and second pressures Pa, Pb, and optionally ambient condition **42** may be used by computer **38** to detect a performance degradation of BOV **12**. In response to detecting such performance degradation of BOV **12**, computer **38** may generate output **44**. In some embodiments, output **44** may include a message to maintenance personnel indicating that a response time of BOV **12** is no longer adequate to meet compressor surge margin requirements, and that maintenance associated with BOV **12** is required. In some embodiments, output **44** may include an annunciation in a cockpit of the aircraft to alert the flight crew. Alternatively or in addition, output **44** may include a signal that initiates a software accommodation onboard the aircraft to mitigate the performance degradation of BOV **12**. Such software accommodation may include computer **38** or other controller of engine **10** imposing one or more restrictions on the operation of engine **10** to reduce the allowable acceleration of engine **10** and thereby reduce the risk of compressor surge for example. Such software accommodation may be activated during flight to permit the aircraft to safely land and, if appropriate, to safely complete its mission.

[0024] FIGS. **2**A and **2**B show an axial cross-section view of an exemplary pneumatic BOV **12** in a closed state and in an open state respectively. BOV **12** may be installed at an intermediate stage of compressor **22** between the inlet of compressor **22** and the outlet of compressor **22**. BOV **12** may be mounted to engine casing **48** defining a radially outer boundary of gas path **46**. BOV **12** may include a movable valve member **50** movably received inside housing **52**. Valve member **50** may be movable (e.g., slidable, translatable) along valve axis VA between the valve-closed position shown in FIG. **2**A and the valve-open position shown in FIG. **2**B. Valve member **50** may be in fluid communication with gas path **46** via an opening defined in casing **48**. In the valve-closed position, valve member **50** may substantially prevent pressurized air from being discharged from gas path **46**. In the valve-open position, valve member **50** may permit pressurized air to be discharged from gas path **46** via outlet **53** formed in housing **52**. In the valve-open position, air may be discharged from outlet **53** to the ambient environment or to another destination. In some embodiments, valve member **50** may be spring-loaded and biased toward the valve-open position.

[0025] BOV **12** may be pneumatically actuated based on a pressure differential across valve member **50**. For example, a radially outer side of valve member **50** relative to gas path **46** may be in fluid communication with a location along gas path **46** that is downstream of BOV **12**. For example, the radially outer side of valve member **50** may be exposed to second pressure Pb at the outlet of compressor **22**. The opposite radially inner side of valve member **50** maybe exposed to intermediate pressure Px at the intermediate position of BOV **12** along compressor **22**. The intermediate position may be located between the inlet and the outlet of compressor **22** so that during normal operation of compressor **22**, second pressure Pb may be greater than intermediate pressure Px (i.e., Pb>Px), and intermediate pressure Px may be greater than first pressure Pa (i.e., Px>Pa). An increase in second pressure Pb relative to intermediate pressure Px may urge valve member **50** toward the valve-closed position. An increase in intermediate pressure Px relative to second pressure Pb may urge valve member **50** toward the valve-open position. The resilient biasing of valve member **50** toward the valve-open position (e.g., provided by a spring) may be calibrated to permit desired modulation of valve member **50** based on a difference between second pressure Pb and intermediate pressure Px.

[0026] BOV **12** may serve to bleed pressurized air from an intermediate station

[0027] of compressor **22** during low and mid power operation. The normal operation of BOV **12** may prevent a compressor instability (e.g., stall or surge) in a location along gas path **46** that is downstream of BOV **12**. The modulation of valve member **50** between the valve-closed position and the valve-open position may be pneumatically actuated (i.e., controlled) based on the magnitudes of second pressure Pb and intermediate pressure Px. In other words, BOV **12** may not be electronically controlled. BOV **12** also may not provide any direct feedback about the axial position of valve member **50** along valve axis VA. In other words, system **13** may be devoid of positional feedback from BOV **12**. Accordingly, positional feedback that could otherwise be available in some electronically controlled valves, may not be available to assess the actuation response time of BOV **12** in response to a change in pressure difference between second pressure Pb and intermediate pressure Px.

[0028] In some situations, BOV **12** can suffer from an increased response time, meaning that BOV **12** may become slower to modulate (close and/or open) for a given change in engine speed (i.e., acceleration or deceleration). The increased response time could be caused by one or more factors such as wear resulting in an increase in sliding friction between valve member **50** and housing **52**, or an inadequate sealing between valve member **50** and housing **52** for example. An increased response time of BOV **12** may be undesirable for engine operability. For example, during an acceleration of the operating speed of engine **10** causing BOV **12** to transition from the valve-open position to the valve-closed position, the increased response time may cause BOV **12** to stay open longer than intended and this may cause engine **10** to suffer from a higher turbine temperature and be exposed to an increased risk of a subsequent sudden closure of BOV **12** causing a non-linear power/thrust increase. During a deceleration of the operating speed of engine **10** causing BOV **12** to transition from the valve-closed position to the valve-open position, the increased response time may cause BOV **12** to remain closed longer than intended and this may cause engine **10** to suffer from a surge/stall instability since BOV **12** would not adequately perform its primary function of offloading one or more stages of compressor **22** upstream of BOV **12**.

[0029] FIG. **3** is another schematic representation of system **13** for detecting the performance degradation of BOV **12**. System **13** may include computer **38** having one or more data processors **54** (referred hereinafter in the singular) and non-transitory machine-readable memory(ies) **56** (referred hereinafter in the singular). Computer **38** may be configured to detect the performance degradation of BOV **12** based on signals acquired via one or more sensors **32**, **34**, **36**, **40**, generate output(s) **44** and optionally also perform other tasks. In some embodiments, computer **38** may be dedicated only to system **13**. Alternatively, computer **38** may include or be part of a controller (e.g., electronic engine controller (EEC)) and may perform additional functions not necessarily associated with system **13**. Computer **38** may receive input(s) such as signal(s) from sensor(s) **32**, **34**, **36**, **40**, perform one or more procedures or steps defined by instructions **58** (e.g., software) stored in memory **56** and executable by processor(s) **54** to generate one or more outputs **44**.

[0030] Processor **54** may include any suitable device(s) configured to cause a series of steps to be performed by computer **38** so as to implement a controller-implemented process such that instructions **58**, when executed by computer **38** or other programmable apparatus, may cause the functions/acts specified in the methods described herein to be executed. Processor(s) **54** 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.

[0031] Memory **56** may include any suitable machine-readable storage medium. Memory **56** may include non-transitory controller 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 **56** may include any storage means (e.g., devices) suitable for retrievably storing machine-readable instructions **58** executable by processor(s).

[0032] One or more thresholds **60** may also be stored in memory **56** or otherwise be available to computer **38** for detecting the mechanical transmission failure.

[0033] Threshold(s) **60** may have the form of a look-up table with rotational speed values and/or ranges of rotational speeds applicable to one or more operating conditions of system **13** and/or of engine **10**.

[0034] FIG. **4** is a flow diagram of an exemplary method **1000** for detecting the performance degradation of BOV **12** or of another bleed-off valve without direct positional feedback from BOV

12. Method **1000** may be performed using system **13** described herein or using another system. For example, machine-readable instructions **58** may be configured to cause computer **38** to perform at least part of method **1000**. Aspects of method **1000** may be combined with aspects of other methods described herein. Method **1000** may be performed when BOV **12** is installed in a compressor section of engine **10** (e.g., in situ). Method **1000** may include elements of system **13**. In various embodiments, method **1000** may include: [0035] operating engine **10** to cause an acceleration of the (e.g., high-pressure) spool of engine **10**, the spool including compressor **22** of engine **10** (block **1002**); [0036] during the acceleration of the spool, acquiring actual first relationship **62**A (shown in FIG. **6**) between the PR across compressor **22** and rotational speed N of the spool (block **1004**); [0037] operating engine **10** to cause a deceleration of the spool (block **1006**); [0038] during the deceleration of the spool, acquiring actual second relationship **64**A (shown in FIG. **6**) between the PR across compressor **22** and rotational speed N of the spool (block **1008**); [0039] determining cross-over rotational speed **66**A (shown in FIG. **6**) corresponding to an intersection of actual first relationship **62**A and actual second relationship **64**A (block **1010**); and [0040] detecting the performance degradation of BOV **12** when cross-over rotational speed **66**A is lower than rotational speed threshold **60** (shown in FIG. **6**) (block **1012**).

[0041] Aspects of method **1000** are describe below in reference to the subsequent figures.

[0042] FIG. **5** is a plot schematically showing an exemplary baseline first relationship **62**B between the PR across at least part of compressor **22** of engine **10** and rotational speed N of the spool including compressor **22** during a relatively high/fast acceleration of the spool, and an exemplary baseline second relationship **64**B between the PR across at least part of compressor **22** of engine **10** and rotational speed N of the spool including compressor **22** during a relatively high/fast deceleration of the spool. The plot of FIG. **5** illustrates a baseline (i.e., nominal) transient behavior of compressor **22** of engine **10** fitted with BOV **12** at an intermediate stage of compressor **22**. One meaningful parameter for engine **10** in operation is the PR, sometimes also referred to as an engine “runline”. An overall PR may be defined as second pressure Pb divided by first pressure Pa (i.e., Pb/Pa) to quantify a total amount of compression provided by compressor **22**.

[0043] In some embodiments, method **1000** may instead use a partial PR that quantifies an amount of compression provided by only a portion (i.e., some but not all the stages) of compressor **22**. In multi-spool engines where the compressor includes two compressor portions that are part of two different spools for example, a spool-specific PR may instead be used. For example, a first PR for a first compressor portion of a first spool may equal the pressure at the outlet of the first compressor portion divided by first pressure Pa, and may be associated with the rotational speed of the first spool. Similarly, a second PR for a second compressor portion of a second spool may equal second pressure Pb divided by the pressure at the inlet of the second compressor portion, and may be associated with the rotational speed of the second spool.

[0044] A steady-state operating line SS is shown as a broken line and illustrates a steady-state operating runline as a function of rotational speed N of the high-pressure spool. In other words, steady-state operating line SS plots PRs obtained at different steady-state rotational speeds N of the high-pressure spool. Baseline first relationship **62**B and baseline second relationship **64**B show runlines for fast accelerations and decelerations respectively from idle speed (low power with BOV **12** open) to maximum power speed (high power with BOV **12** closed).

[0045] Following first arrows **68** shown in broken lines during an acceleration of the high-pressure spool, baseline first relationship **62**B (at a particular speed) is initially higher than steady-state operating line SS because of the excess fuel used to accelerate engine **10** and raise second pressure Pb. However, eventually baseline first relationship **62**B falls below steady-state operating line SS. This is caused by BOV **12** having a finite response time that takes an amount of time to close, and is therefore lagging from its steady-state position. The additional bleed air compared to the steady state position causes second pressure Pb to be reduced and thus the baseline first relationship **62**B falls below the steady-state operating line SS.

[0046] Following second arrows **70** shown in solid lines during the deceleration, baseline second relationship **64**B (at a particular speed) is initially higher than steady-state because BOV **12** is closed to a greater degree than for its steady-state position. This results in less bleed less air and thus temporarily keeping second pressure Pb and baseline second relationship **64**B higher than steady-state operating line SS. Eventually, as BOV **12** reaches a fully-open configuration, baseline second relationship **64**B falls below steady-state operating line SS because of the fuel flow reduction that is used to decelerate engine **10**. By comparison, in an engine without BOV **12**, the acceleration runline would always be higher (at a speed) than steady-state operating line SS and the deceleration runline would always be lower than steady-state operating line SS. The runline inversion characteristic that is shown in FIG. **5** between baseline first relationship **62**B and baseline second relationship **64**B is caused by the finite response time of BOV **12** located at an intermediate (i.e., interstage) position along compressor **22**.
[0047] It can be observed that baseline first relationship **62**B and baseline second relationship **64**B during acceleration and deceleration respectively intersect each other at baseline cross-over rotational speed **66**B, which may be around a mid-point between the low power idle speed and the maximum power speed. Baseline cross-over rotational speed **66**B may be used in method **1000** to detect a performance degradation of BOV **12** because baseline cross-over rotational speed **66**B is directly related to the response time of BOV **12** for a given operating condition of engine **10**. The term “baseline” in baseline first relationship **62**B, baseline second relationship **64**B and baseline cross-over rotational speed **66**B is intended to represent characteristics of a BOV having an adequate (e.g., optimal) performance. For example, in some embodiments, engine **10** having a new BOV **12** may be operated to generate baseline first relationship **62**B and baseline second relationship **64**B so that baseline cross-over rotational speed **66**B may be determined for that specific BOV **12** and engine combination. In some embodiments, a more universal baseline cross-over rotational speed **66**B may be obtained from a manufacturer of BOV **12** and of the engine **10** then used in method **1000** to assess the performance of BOV **12**. In some embodiments, baseline cross-over rotational speed **66**B may be obtained from modeling and simulation, or may be determined in an empirical manner.
[0048] FIG. **6** is a plot schematically showing an exemplary actual first relationship **62**A between the PR across at least part of compressor **22** of engine **10** and rotational speed N of the spool including compressor **22** during a relatively high/fast acceleration of the spool, and an exemplary actual second relationship **64**A between the PR across at least part of compressor **22** of engine **10** and rotational speed N of the spool including compressor **22** during a relatively high/fast deceleration of the spool. Baseline first relationship **62**B and baseline second relationship **64**B are also shown in FIG. **6** for comparison with actual first relationship **62**A and actual second relationship **64**A.
[0049] Actual first relationship **62**A and actual second relationship **64**A may be acquired and used in the assessment of BOV **12** only when the acceleration and deceleration are each sufficiently high to exhibit the cross-over (inversion) behaviour that produces cross-over rotational speed **66**A at the intersection of actual first relationship **62**A and actual second relationship **64**A. In some embodiments, one or more acceleration and/or deceleration thresholds may be used to determine if the acceleration and deceleration are adequate for actual first relationship **62**A and actual second relationship **64**A to be used in method **1000**. For example, method **1000** may include determining that an acceleration rate of the spool during the acceleration of the spool meets an acceleration criterion (e.g., the acceleration rate meets or exceeds an acceleration threshold). Method **1000** may also include determining that a deceleration rate of the spool during the deceleration of the spool meets a deceleration criterion (e.g., the deceleration rate meets or exceeds a deceleration threshold). In some embodiments, the determination of whether the acceleration and/or deceleration are sufficient fast could be based on a prescribed time criterion such as faster than **5** seconds from idle speed to the speed at maximum power, or a pilot-input criterion determined from a magnitude and

duration of a pilot input received via power/thrust lever for example.
[0050] In some embodiments, actual first relationship **62**A and actual second relationship **64**A may not necessarily extend entirely from the idle speed to the maximum power speed. In some embodiments, actual first relationship **62**A and actual second relationship **64**A may only extend partially between the idle speed to the maximum power speed. For example, engine **10** may be operated to cause the acceleration and the deceleration of the spool between first and second rotational speeds that are sufficiently far apart to cause modulation of BOV **12** so that actual cross-over rotational speed **66**A may be determined and compared against rotational speed threshold **60**. In other words, the first and second rotational speeds may be selected so that actual cross-over rotational speed **66**A is between the first and second rotational speeds.
[0051] Actual first relationship **62**A may differ from baseline first relationship **62**B during the otherwise same or similar operating conditions due to a performance degradation (e.g., reduced response time, unacceptable lag, slow modulation time) of BOV **12**. Similarly, actual second relationship **64**A may differ from baseline second relationship **64**B during the otherwise same operating conditions due to the same performance degradation of BOV **12**. In the actual (current) degraded condition, BOV **12** may close later (i.e., at higher rotational speed N) during acceleration and may reopen later (i.e., at lower rotational speed) during deceleration. This results in shifting actual cross-over rotational speed **66**A toward the left in FIG. **6** to a lower rotational speed N compared to baseline cross-over rotational speed **66**B. Actual cross-over rotational speed **66**A may correspond to the intersection of actual first relationship **62**A with actual second relationship **64**A. The magnitude of the downward shift of actual cross-over rotational speed **66**A from baseline cross-over rotational speed **66**B may then be used to assess the performance of BOV **12** and, when applicable, detect the performance degradation of BOV **12** caused by the increased response time of BOV **12** in response to a change in pressure differential (e.g., Pb-Px) across valve member **50** of BOV **12**.
[0052] Method **1000** may detect the performance degradation when actual cross-over rotational speed **66**A is outside a prescribed margin M away from baseline cross-over rotational speed **66**B. Prescribed margin M may be defined by rotational speed threshold **60** stored in memory **56**. Rotational speed threshold **60** may be determined by subtracting a prescribed value from baseline cross-over speed **66**B. In some embodiment, the performance degradation may be detected when actual cross-over rotational speed **66**A of the high-pressure spool is lower than rotational speed threshold **60** meaning that the performance of BOV **12** may no longer be optimal or acceptable and a maintenance action may be required.
[0053] Rotational speed threshold **60** may be static, i.e., constant in all operating conditions. Alternatively, rotational speed threshold **60** may be variable to accommodate different operating conditions. For example, rotational speed threshold **60** may be retrieved from a look-up table stored in memory **56** based on a parameter associated with engine **10** and that may influence actual cross-over rotational speed **66**A. For example, rotational speed threshold **60** may be variable as a function of an ambient condition in which engine **10** is operating. The ambient condition may include an outside temperature, an altitude of an aircraft being propelled by engine **10** and/or an airspeed of the aircraft.
[0054] In some embodiments, method **1000** may be performed by an EEC of engine **10** and may be performed live (i.e., in real-time) during flight of the aircraft to which engine **10** is mounted. In the event of a detection of an unacceptable performance degradation of BOV **12**, method **1000** may include generating an annunciation in the cockpit of the aircraft to alert the flight crew. In some embodiments, method **1000** may be performed in a post-flight data processing algorithm using computer **38**, which may be separate from the EEC.
[0055] FIG. **7** is a flow diagram of another exemplary method **2000** for detecting the performance degradation of BOV **12** or of another bleed-off valve without direct positional feedback from BOV **12**. Method **2000** may be performed using system **13** described herein or using another system. For

example, machine-readable instructions **58** may be configured to cause computer **38** to perform at least part of method **2000**. Aspects of method **2000** may be combined with aspects of method **1000** described above. Method **2000** may be performed when BOV **12** is installed in a compressor section of engine **10** (e.g., in situ). Method **2000** may include elements of system **13**.

[0056] At block **2002**, a sufficiently fast acceleration of engine **10** may be detected and actual first relationship **62**A may be recorded by computer **38** at block **2004**. At block **2006**, a sufficiently fast deceleration of engine **10** may be detected and actual second relationship **64**A may be recorded by computer **38** at block **2008**. At block **2010**, actual first relationship **62**A and actual second relationship **64**A may be combined together to subsequently determine actual cross-over rotational speed **66**A at block **2012**. Actual cross-over rotational speed **66**A may correspond to the intersection point of actual first relationship **62**A and actual second relationship **64**A where the PR of actual first relationship **62**A during acceleration is substantially equal to the PR of actual second relationship **64**A during deceleration. In various embodiments, actual first relationship **62**A and actual second relationship **64**A may be recorded in different orders and not necessarily one immediately after the other.

[0057] At block **2014**, actual cross-over rotational speed **66**A is compared to rotational speed threshold **60** to determine if an undesirable performance degradation exists with BOV **12**. For example, if actual cross-over rotational speed **66**A is below rotational speed threshold **60** (e.g., 75% of the rotational speed at maximum power output), an undesirable performance degradation (e.g., increased response time) may be detected. Prescribe margin M (shown in FIG. **6**) and hence rotational speed threshold **60** may be established based on engine testing and characterisation to determine a maximum amount of increased time response of BOV **12** that can be tolerated during operation of engine **10**, and in consideration of engine-to-engine variability as well as the accuracy of sensor(s) **32**, **34**, **36**, **40**. The 75% value is only an example of a speed threshold. Each engine **10** has a 100% speed value (e.g., 100% =50,000 rpm) which may be different for each engine model and which may be defined as the aero design speed point (i.e., not necessarily the maximum rotational speed).

[0058] If no performance degradation is detected, the normal operation of engine **10** may continue at block **2016** and no corrective action may be required. However, if an unacceptable performance degradation is detected, an annunciation may be generated in the cockpit, a maintenance action may be performed, and/or a software (SW) accommodation may be executed as explained above.

[0059] FIG. **8** is a flow diagram of another exemplary method **2000**A for detecting the performance degradation of BOV **12** or of another bleed-off valve without direct positional feedback from BOV **12**. Method **2000**A may be performed using system **13** described herein or using another system. For example, machine-readable instructions **58** may be configured to cause computer **38** to perform at least part of method **2000**A. Aspects of method **2000**A may be combined with aspects of method **1000** described above. Method **2000**A may be performed when BOV **12** is installed in a compressor section of engine **10** (e.g., in situ). Method **2000**A may include elements of system **13**. Method **2000**A may include steps/actions of method **2000** and like blocks are identified using like reference numerals.

[0060] Method **2000** described above may use a fixed rotational speed threshold **60** that is universal for this type (i.e., model number) of BOV **12** and this type (i.e., model number) of engine **10**. In other words, rotational speed threshold **60** may be universal and applicable to a plurality of engines. However, method **2000**A may instead use a rotational speed threshold **60** that is tailored for this specific combination of engine **10** (e.g., serial no. 1234) and BOV **12**. The engine-specific rotational speed threshold **60** may then take into account engine-to-engine variations. For example, method **2000**A may instead detect a shift in cross-over speed from baseline cross-over rotational speed **66**B determined during an initial engine run cross-over speed detection. The steps/actions in box A in dashed line may be performed only during a specific engine first run (e.g., on production acceptance pass-off) when engine **10** and BOV **12** are in a newer state with less utilization and suitable to establish an acceptable baseline.

[0061] At block **2020**, a sufficiently fast acceleration of engine **10** may be detected and baseline first relationship **62**B may be recorded by computer **38** at block **2022**. At block **2024**, a sufficiently fast deceleration of engine **10** may be detected and baseline second relationship **64**B may be recorded by computer **38** at block **2026**. At block **2028**, baseline first relationship **62**B and baseline second relationship **64**B may be combined together to subsequently determine baseline cross-over rotational speed **66**B at block **2030**. Baseline cross-over rotational speed **66**B may correspond to the intersection point of baseline first relationship **62**B and baseline second relationship **64**B where the PR of baseline first relationship **62**B during acceleration is substantially equal to the PR of baseline second relationship **64**B during deceleration.

[0062] At block **2032**, baseline cross-over rotational speed **66**B may stored in (e.g., non-volatile) memory **56**, in a log book, or in another database. At block **2034**, baseline cross-over rotational speed **66**B may be retrieved and used in block **2014** with an acceptable margin M. In block **2014**, actual cross-over rotational speed **66**A is then compares to baseline cross-over rotational speed **66**B retrieved from memory **56** and combined with margin M. For example, baseline cross-over rotational speed **66**B for engine serial no. 1234 could be 81% of the speed at maximum power output during the first engine run and margin M of about 3% may be deemed allowed for any engine of the same type. For this specific engine (i.e., serial no. 1234), the detection of the performance degradation would then happen when actual cross-over rotational speed 66A is equal to or less than 78% (i.e., 81% minus 3%) of the speed at maximum power output. The use of an engine-specific rotational speed threshold **60** may be more complex but more sensitive due to the engine-to-engine variability being accounted for to potentially allow the use of a smaller margin M.

[0063] 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.

Claims

1. A method for detecting a performance degradation of a pneumatic bleed-off valve installed in a compressor section of a gas turbine engine, the method comprising: operating the gas turbine engine to cause an acceleration of a spool of the gas turbine engine from a first rotational speed to a second rotational speed, the spool including a compressor of the gas turbine engine; during the acceleration of the spool, acquiring a first relationship between a pressure ratio across the compressor and a rotational speed of the spool; operating the gas turbine engine to cause a deceleration of the spool from the second rotational speed to the first rotational speed; during the deceleration of the spool, acquiring a second relationship between the pressure ratio across the compressor and the rotational speed of the spool; determining a cross-over rotational speed corresponding to an intersection of the first relationship and the second relationship, the cross-over rotational speed being between the first rotational speed and the second rotational speed; and detecting the performance degradation of the pneumatic bleed-off valve when the cross-over rotational speed is lower than a rotational speed threshold.

2. The method as defined in claim 1, wherein the performance degradation is an increased response time of the pneumatic bleed-off valve.

3. The method as defined in claim 1, comprising restricting an allowable acceleration of the gas turbine engine after detecting the performance degradation.

4. The method as defined in claim 1, wherein the pressure ratio across the compressor is an overall pressure ratio across an entirety of the compressor.

5. The method as defined in claim 1, wherein the pressure ratio across the compressor is a pressure ratio across only part of the compressor less than an entirety of the compressor.

6. The method as defined in claim 1, wherein the method is performed during flight of an aircraft propelled by the gas turbine engine.
7. The method as defined in claim 1, wherein the rotational speed threshold is universal for a plurality of gas turbine engines.
8. The method as defined in claim 1, wherein the rotational speed threshold is variable based on an ambient condition in which the gas turbine engine is operating.
9. The method as defined in claim 1, comprising: receiving an engine-specific baseline cross-over rotational speed exhibited by the pneumatic bleed-off valve installed in the gas turbine engine when the pneumatic bleed-off valve was in a new state; and determining the rotational speed threshold based on the engine-specific baseline cross-over rotational speed.
10. The method as defined in claim 9, wherein determining the rotational speed threshold includes subtracting a prescribed value from the engine-specific baseline cross-over rotational speed.
11. The method as defined in claim 1, comprising, before detecting the performance degradation: determining that an acceleration rate of the spool during the acceleration of the spool meets an acceleration criterion; and determining that a deceleration rate of the spool during the deceleration of the spool meets a deceleration criterion.
12. A method for detecting a slow modulation time of a pneumatically-actuated bleed-off valve without positional feedback from the bleed-off valve, the bleed-off valve being installed at an intermediate stage of a compressor section of a gas turbine engine, the method comprising: operating the gas turbine engine to cause an acceleration of a spool of the gas turbine engine from a first rotational speed to a second rotational speed, the spool including a compressor of the gas turbine engine; during the acceleration of the spool: causing the bleed-off valve to transition from an open position to a closed position; and acquiring a first relationship between a pressure ratio across the compressor and a rotational speed of the spool; operating the gas turbine engine to cause a deceleration of the spool from the second rotational speed to the first rotational speed; during the deceleration of the spool: causing the bleed-off valve to transition from the closed position to the open position; and acquiring a second relationship between the pressure ratio across the compressor and the rotational speed of the spool; determining a cross-over rotational speed corresponding to an intersection of the first relationship and the second relationship, the cross-over rotational speed being between the first rotational speed and the second rotational speed; and detecting the slow modulation time of the bleed-off valve when the cross-over rotational speed is lower than a rotational speed threshold.
13. The method as defined in claim 12, comprising: while operating the gas turbine engine with the bleed-off valve in a new state, determining a baseline cross-over rotational speed specifically associated with the bleed-off valve in the new state; and before detecting the slow modulation time of the bleed-off valve, determining the rotational speed threshold by adding a margin to the baseline cross-over rotational speed.
14. The method as defined in claim 12, wherein: the slow modulation time of the pneumatically-actuated bleed-off valve is detected during flight of an aircraft propelled by the gas turbine engine; and the method includes generating an annunciation in response to detecting the slow modulation time.
15. The method as defined in claim 14, comprising, before detecting the slow modulation time of the pneumatically-actuated bleed-off valve: determining that an acceleration rate of the spool during the acceleration of the spool meets an acceleration criterion; and determining that a deceleration rate of the spool during the deceleration of the spool meets a deceleration criterion.
16. A system for detecting a performance degradation of a pneumatic bleed-off valve installed in a compressor section of a gas turbine engine, the system comprising: sensors configured to acquire: a rotational speed of a spool of the gas turbine engine, the spool including a compressor of the gas turbine engine; and a pressure ratio across the compressor; one or more data processors; and non-transitory machine-readable memory storing: a first relationship between a pressure ratio across the

compressor and the rotational speed of the spool acquired during an acceleration of the spool using the sensors; a second relationship between the pressure ratio across the compressor and the rotational speed of the spool acquired during a deceleration of the spool using the sensors; and instructions executable by the one or more data processors and configured to cause the one or more data processors to: determine a cross-over rotational speed corresponding to an intersection of the first relationship and the second relationship; and detect the performance degradation of the pneumatic bleed-off valve when the cross-over rotational speed is lower than a rotational speed threshold.

17. The system as defined in claim 16, wherein the one or more data processors are part of a controller of the gas turbine engine and disposed onboard an aircraft propelled by the gas turbine engine.

18. The system as defined in claim 16, wherein: the non-transitory machine-readable memory stores an engine-specific baseline cross-over rotational speed exhibited by the pneumatic bleed-off valve when the pneumatic bleed-off valve was in a new state; and the instructions are configured to cause the one or more data processors to determine the threshold based on the engine-specific baseline cross-over rotational speed.

19. The system as defined in claim 16, wherein: the sensors are configured to acquire an ambient condition in which the gas turbine engine is operating; and the instructions are configured to cause the one or more data processors to determine the threshold based on the ambient condition.

20. The system as defined in claim 16, wherein the system is devoid of positional feedback from the pneumatic bleed-off valve.