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Inventor(s)	Eller; Erez et al.

ROTOR CONTROL FOR A CONVERTIBLE AIRCRAFT

Abstract

An aircraft includes a body having a fuselage and a wing assembly, a main shaft supported for rotation with respect to the body about a rotor axis, and a blade assembly coupled to the main shaft for corotation therewith. The blade assembly includes a rotor hub and a plurality of blades circumferentially spaced about the rotor hub. Each blade is coupled to the rotor hub for rotation about a respective blade axis. The aircraft includes a pitch control system coupled to the blade assembly to rotate each blade about the respective blade axis. The pitch control system includes a slider, a swashplate, a first actuator coupled to the slider, and a second actuator operable to rotate the swashplate assembly with respect to the slider.

Inventors: **Eller; Erez (Plymouth, CT), Lauder; Timothy F. (Oxford, CT), Hood; Richard Thomas (Fairfield, CT), Miner; Frederick John (Barkhamsted, CT), Anderson; Brian (Aledo, TX)**

Applicant: **Lockheed Martin Corporation** (Bethesda, MD)

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Background/Summary

FIELD OF INVENTION

[0001] Embodiments described herein relate to control systems for rotor assemblies, and specifically pitch control systems for rotor systems of aircraft.

BACKGROUND

[0002] Aircraft, and specifically vertical take-off and landing (VTOL) aircraft, utilize thrusters (e.g., a rotor system) to provide lift, control, and thrust during flight operations. A convertible VTOL aircraft, such as a tiltrotor, tail-sitter, or tiltwing aircraft, is capable of both thruster powered flight, in which thrusters provide a combination of lift, control, and thrust, and wing powered flight, in which aerodynamic profiles (for example, the airfoils of the wings) provide the lift and the thrusters primarily provide thrust and control. The thrusters (e.g., rotors, propellers, etc.) may include a blade assembly capable of variable blade pitch control. The blade pitch may be controlled by a pitch control system. Typical control systems used on fly-by-wire VTOL aircraft electronically process control input (e.g., from a pilot in a cockpit) and transmit an electronically mixed control signal to a common set of actuators configured to achieve both collective pitch control and cyclic pitch control of the blade assembly, for example by adjusting the length of each actuator individually to control the position and orientation of a swashplate. Systems for adjusting collective pitch especially require high stiffness, reliability, and resolution to enable the accurate pitch control that is required by some aircraft configurations, particularly convertible aircraft configurations. However, conventional methods using common actuators can reduce sensitivity, introduce slop, add weight, and increase maintenance costs. Additionally, typical control systems with common actuators can create off-axis loads that increase friction and sticking during pitch change operations.

SUMMARY

[0003] Embodiments described herein provide an aircraft including a body having a fuselage and a wing assembly, a main shaft supported at the body for rotation with respect to the body about a rotor axis, and a blade assembly coupled to the main shaft for corotation therewith. The blade assembly includes a rotor hub and a plurality of blades circumferentially spaced about the rotor hub. Each blade is coupled to the rotor hub for rotation about a respective blade axis. The aircraft includes a pitch control system coupled to the blade assembly to rotate each blade about the respective blade axis. The pitch control system includes a slider, a swashplate, a first actuator and a second actuator. The slider is coupled to the main shaft for translation along the rotor axis. Translation of the slider rotates each blade about the respective blade axis by an equal amount. The swashplate assembly is coupled to the slider for rotation about a tilt axis substantially perpendicular to the rotor axis. Rotation of the swashplate assembly about the tilt axis rotates each blade about the respective blade axis by a different amount. The first actuator is coupled to the slider and includes a first link pivotally coupled to the body, a pivot link pivotally coupled to the body and having a pivot point movable with respect to the body, and a lever arm rotatably coupled to the pivot link for rotation about the pivot point according to movement of the first link. The second actuator is operable to rotate the swashplate assembly with respect to the slider. The second actuator includes a second link pivotally coupled to the slider and pivotally coupled to the swashplate assembly. The first link is configured to vary a length thereof to rotate the lever arm about the pivot point and translate the slider along the rotor axis. The second link is configured to vary a length thereof to rotate the swashplate assembly about the tilt axis.

[0004] A pitch control system is configured to change a pitch of a blade assembly mounted on a main shaft for rotation about a rotor axis. The pitch control system includes a slider configured to couple to the main shaft for translation along the rotor axis, a slider actuator operable to translate the slider with respect to the main shaft, a swashplate assembly coupled to the slider for rotation about a tilt axis substantially perpendicular to the rotor axis, and a swashplate actuator operable to rotate the swashplate assembly with respect to the slider. The slider actuator is mounted between a

fixed body and the slider. The swashplate actuator is mounted between the slider and the swashplate assembly. The slider actuator and the swashplate actuator are independently operated.
[0005] Other aspects will become apparent by consideration of the detailed description and accompanying drawings.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0006] FIG. **1** illustrates an aircraft according to an exemplary embodiment in a first mode that may be used during take-off and hover operations.
[0007] FIG. **2** illustrates the aircraft of FIG. **1** in a second mode that may be used for forward flight operations.
[0008] FIG. **3** is a perspective view of a rotor system for use with the exemplary aircraft of FIG. **1**, the rotor system including a pitch control system.
[0009] FIG. **4** is a cross-sectional view of the rotor system of FIG. **3**.
[0010] FIG. **5** is a side view of the rotor system of FIG. **3**, the rotor system including a rotor head (illustrated schematically), and with the pitch control system in a neutral configuration.
[0011] FIG. **6** is a side view of the rotor system of FIG. **3** illustrating the pitch control system during a collective pitch change.
[0012] FIG. **7** is a side view of the pitch control system of FIG. **3** illustrating the pitch control system during a cyclic pitch change.
[0013] FIG. **8** illustrates a control system of the aircraft of FIG. **1** for controlling the pitch control system of FIG. **3**.
DETAILED DESCRIPTION
[0014] Before any embodiments are explained in detail, it is to be understood that the embodiments described herein are provided as examples and the details of construction and the arrangement of the components described herein or illustrated in the accompanying drawings should not be considered limiting. Also, it is to be understood that the phraseology and terminology used herein is for the purpose of description and should not be regarded as limited. The use of “including,” “comprising” or “having” and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. The terms “mounted,” “connected” and “coupled” are used broadly and encompass both direct and indirect mounting, connecting, and coupling. Further, “connected” and “coupled” are not restricted to physical or mechanical connections or couplings, and may include electrical connections or couplings, whether direct or indirect. Also, electronic communications and notifications may be performed using any known means including direct connections, wireless connections, and the like.
[0015] FIGS. **1** and **2** illustrate a vertical take-off and landing (VTOL) aircraft **10**. The aircraft **10** is a convertible aircraft capable of rotor or thruster powered flight and wing powered flight. In the illustrated embodiment, the aircraft **10** is a tail-sitter aircraft. The aircraft **10** is exemplary and the teachings included herein can be incorporated into other types of convertible aircraft or other types of VTOL rotorcraft. The aircraft **10** includes a body **12** having a fuselage **14** extending along a longitudinal axis L between a nose **18** and a base **22**, and a wing assembly **26** coupled to extend from the fuselage **14** transverse to the longitudinal axis L. In the illustrated embodiment, the aircraft **10** is symmetrical and the wing assembly **26** includes a first wing **28** and a second wing **30** positioned on an opposite side of the fuselage **14** from the first wing **28**.
[0016] The aircraft **10** may be referred to using directional terminology including referring to a direction along the longitudinal axis L toward the nose **18** as a forward direction or toward the front and a direction along the longitudinal axis L toward the base **22** as a rearward direction or toward the rear. Directions leading away from the longitudinal axis L may be referred to as outward or

distal and directions leading toward the longitudinal axis L may be referred to as inward or proximal. This terminology is not intended to be limiting and is merely used for the sake of description.

[0017] With reference to FIG. **1**, the aircraft **10** includes thrusters **34** coupled to the wing assembly **26** to provide lift and thrust to the aircraft **10**. In this context, a thruster is a component or group of components capable of generating forces and moments to provide the aircraft with a means of thrust, lift, and/or control. In the illustrated embodiment, the first wing **28** and the second wing **30** of the aircraft **10** each include a thruster **34** coupled thereto. In some embodiments, the aircraft **10** includes multiple thrusters **34** on each wing **28**, **30**. In some embodiments, the aircraft **10** additionally or alternately includes one or more thrusters **34** on the fuselage **14**. In the illustrated embodiment, the thrusters **34** each include an outer housing **38** (also referred to herein as a nacelle **38**) supporting a rotor system **42**. The rotor system **42** includes a blade assembly **46**, also referred to herein as a rotor head assembly **46**, supported at a front end of the nacelle **38** and configured to rotate about a rotor axis R. In some embodiments, the rotor system **42** may include multiple blade assemblies **46**. The blade assembly **46** includes rotor hub **82** (FIG. **5**) and a plurality of blades **50**. Rotation of the blades **50** about the rotor axis R generates lift, thrust, and moments or a combination thereof that fly and control the aircraft **10** based on a pitch of the blades **50**. Each of the blades **50** is rotatable relative to the rotor hub **82** about a respective blade axis B (FIG. **5**) to create pitch. The rotor system **42** further includes a drivetrain **64** connecting the rotor head **46** to a prime mover **52**. The prime mover **52** may be an engine or other type of generator capable of transmitting rotation to the rotor systems **42**. The drivetrain **64** includes at least one gearbox **66** and one or more other gearboxes, transmissions, or other parts capable of transferring power from the prime mover **52** to the rotor head **46**. In the illustrated embodiment, the prime mover **52** is positioned in the fuselage **14** of the aircraft **10** and provides power to both thrusters **34** to rotate the blade assemblies **46**. A portion of the drivetrain **64** extends through the wings **28**, **30** to connect the prime mover **52** with the thrusters **34**. Many configurations are possible and the illustrated configuration is provided as an example only. For example, in some embodiments, the aircraft **10** may include multiple prime movers **52** and/or may include dedicated prime movers **52** for each thruster **34**. In some embodiments the prime mover(s) **52** may be positioned elsewhere on the aircraft **10**, for example, in the wing assembly **26** or partially or entirely surrounded by the nacelle **38** of one of the thrusters **34**. Still further configurations may be used.

[0018] With continued reference to FIG. **1**, the nacelle **38** of each thruster **34** surrounds the rotor system **42** to protect the internal components from the environment. The nacelle **38** has an aerodynamic outer shape or profile to minimize drag along the longitudinal axis L of the aircraft **10**. As referenced above, in the illustrated embodiment, the aircraft **10** is a tail-sitter type aircraft and the aircraft **10** includes tail fins **54** extending rearwardly and laterally outwardly from the wing assembly **26** to create a wide base. The tail fins **54** are each equipped with one or more retractable landing gears **56** configured to engage a ground surface to support the aircraft **10** in an upright orientation when the aircraft **10** is grounded, as shown in FIG. **1**. In the illustrated embodiment, the aircraft **10** includes two of the tail fins **54**, each aligned with one of the thrusters **34** and extending from the nacelle **38** thereof to create a continuous and aerodynamic outer profile. In other embodiments, the aircraft **10** may include more tail fins **54** and the tail fins **54** may be spaced from the nacelles **38** along the wing assembly **26**.

[0019] The aircraft **10** is operable in a first mode, shown in FIG. **1**, and a second mode, shown in FIG. **2**. In the first mode, the aircraft **10** is in the upright orientation and the longitudinal axis L extends generally vertically. The first mode may be a thruster powered flight mode and the thrusters **34** may be operated to provide a combination of lift and thrust. The first mode may be used to allow the aircraft **10** to take off and land vertically, and to hover in the upright orientation. In the first mode, the thrusters **34** provide all or almost all the lift and thrust to the aircraft **10**. In the second mode, the aircraft **10** is in a level orientation and the longitudinal axis L extends generally horizontally. The second mode may be a wing powered flight mode and the thrusters **34** may be operated to provide additional thrust and balance to the aircraft **10**. The majority of the lift comes from the aerodynamic profile of the body **12** of the aircraft **10**, primarily the wing assembly **26** with additional lift from the fuselage **14**. The second mode may be used to allow the aircraft **10** to perform forward flight operations.

[0020] With reference to FIG. **3**, the rotor system **42** of one of the thrusters **34** is illustrated in more detail. As discussed above, the rotor system **42** includes a drivetrain that couples the blade assembly **46** to the prime mover **52**. In the illustrated embodiment, the gearbox **66** is positioned within the nacelle **38** and the gearbox **66** includes a gearbox casing **70** and one or more gear mechanisms or transmissions (not shown) positioned within the casing **70** and rotatably driven by the prime mover **52**. The gear mechanisms may scale the speed and torque before transmitting the rotation to an output, such as a main shaft **74**. The main shaft **74** extends along the rotor axis R to a forward end **78** (FIG. **5**) and is supported in the casing **70** by bearings (not shown) for rotation about the rotor axis R. The rotor head **46** is supported on the forward end **78** of the main shaft **74**.

[0021] Turning to FIG. **3-5**, the rotor systems **42** of the thrusters **34** are variable pitch rotors that can vary the amount and direction of force provided to the aircraft **10** by changing a pitch of the blade assembly **46**. The overall pitch of the blade assembly **46** is controlled by an associated pitch control system **62** that rotates the blades **50** to change a blade pitch thereof. The pitch control system **62** may be part of or connected to a larger rotor control system and/or a larger aircraft control system **300** (FIG. **8**) that is capable of controlling the rotation speed and additional characteristics of the rotor system **42** not affected by the pitch control system **62**. The pitch control system **62** includes a collective control assembly **94** and a cyclic control assembly **98**, which are independently operable to rotate the blades **50** and change the pitch of the blade assembly **46**.

[0022] The collective control assembly **94** includes a first actuator **102** and a slider **106**. The slider **106**, also referred to herein as a collective slider **106**, is supported on a slider guide inside the nacelle **38** to translate with respect to the blade assembly **46** along the rotor axis R. In the illustrated embodiment, the slider **106** is generally cylindrical and is mounted to a cylindrical upper portion **110** of the casing **70** by bearings (not shown) to surround the main shaft **74**. The main shaft **74** extends within the upper portion **110** of the casing **70** and the upper portion **110** and the slider **106** are coaxial with the shaft **74** and the rotor axis R. In some embodiments, the slider **106** is coupled directly to the main shaft **74** by bearings for translation along the main shaft **74**. The slider **106** is a non-rotating component and is fixed against rotation about the rotor axis R with respect to the body **12** of the aircraft **10**. In some embodiments, the slider guide, in this case the upper portion **110**, may include a track or groove to prevent rotation of the slider **106**. In some embodiments, the slider **106** is prevented from rotating by the lever arm **118** and pivot link **122** of the first actuator **102**. The main shaft **74** therefore rotates with respect to the slider **106**. Movement of the slider **106** along the rotor axis R alters the pitch of the blade assembly **46** collectively, or causes a collective pitch change.

[0023] With continued reference to FIGS. **3-5**, in the illustrated embodiment, the first actuator **102** is coupled between the casing **70** of the gearbox **66** and the slider **106**. In some embodiments, the first actuator **102** may be coupled between the slider **106** and another fixed part of the aircraft. The first actuator **102** is operable to move the slider **106** along the rotor axis R and may also be referred to as the collective actuator or the slider actuator. The first actuator **102** includes a first link **114**, a lever arm **118**, and a pivot link **122**. The first link **114** includes a first electro-mechanical actuator **124** (EMA). The first EMA **124** is operable to change a length of the first link **114**, or in other words, to change the distance between a first end **126** and a second end **130** of the first link **114**. The first EMA **124** may be operated to expand (i.e., increase the length of the first link **114** and increase the distance between the first end **126** and the second end **130**) or to retract (i.e., decrease the length of the first link **114** and decrease the distance between the first end **126** and the second end **130**). The first EMA **124** may be any type of actuator capable of varying a length thereof (e.g., linear, rotary, etc.). In the illustrated embodiment, the first EMA **124** includes one or more motors **134** configured to rotate, a transmission **138** that converts rotation from the motor(s) **134** into translation, and an output shaft **142** that translates in response to rotation of the motors **134**. The transmission **138** may include a ball screw, a lead screw, a belt drive, or any other mechanism for converting rotation to translation. In some embodiments, the motors may be oriented so that an axis of rotation is parallel to the first link **114** and the direction of expansion. In other embodiments, the motors may be oriented so that the axis of rotation is perpendicular to the first link and the direction of expansion. The motors **134** may be operable in forward and reverse to expand and retract the first EMA **124**. In the illustrated embodiment, the first EMA **124** is oriented with the output shaft **142** extending forward and an end of the output shaft **142** forms the second end **130** of the first link **114**. In other embodiments, other orientations or configurations may be used.

[0024] In the illustrated embodiment, the first end **126** of the first link **114** is coupled to a first mounting point **146** on the gearbox **66**. In some embodiments, the first end **126** connects to another fixed portion of the aircraft **10**, such as the body **12**, an inner frame, or other structure within the nacelle **38** or of the body **12**. The first mounting point **146** is a pivot bracket with aligned openings integrally formed in the casing **70** of the gearbox **66**. The first end **126** is pivotally coupled to the first mounting point **146** (e.g., by a pin). Thus, the first link **114** is rotatable with respect to the gearbox **66** about the first mounting point **146**. The second end **130** of the first link **114** is pivotally coupled to the lever arm **118**.

[0025] With continued reference to FIGS. **3-5**, the lever arm **118** is coupled between the first link **114** and the slider **106** to transmit movement of the first link **114** to the slider **106** to move the slider **106** along the rotor axis R. The lever arm **118** extends between a first lever end **150** and a second lever end **154**. The first lever end **150** is pivotally coupled to the second end **130** of the first link **114** (e.g., by a pin) so that the lever arm **118** rotates with respect to the first link **114** about the second end **130**. The second lever end **154** is pivotally coupled to the slider **106**, to allow rotation of the lever arm **118** with respect to the slider **106**. As seen best in FIG. **3**, the lever arm **118** is ‘fork’ shaped and partially surrounds the slider **106**. In other words, the second lever end **154** is U-shaped and split into two branches that are positioned on either side of the slider **106**. The second lever end **154** is coupled to the slider **106** on either side (e.g., by a pair of pins) for rotation about a slider pivot axis **156** that intersects the rotor axis R. The slider pivot axis **156** is perpendicular to the rotor axis R.

[0026] As best seen in FIG. **4**, the lever arm **118** further includes a fulcrum point **158** about which the lever arm **118** rotates. The fulcrum point **158** (also referred to herein as the pivot point **158**) is positioned between the first lever end **150** and the second lever end **154**. In the illustrated embodiment, the fulcrum point **158** is approximately centered along the length of the lever arm **118**. In other embodiments, the fulcrum point **158** may be positioned at other locations between the first lever end **150** and the second lever end **154** and the position may be selected to achieve a desired mechanical advantage, for example, to achieve a desired range of motion of the slider **106** given the capabilities of the selected EMA. The lever arm **118** and the provided mechanical advantage also allows the system to be optimized for precision, for power, or for range based on the specific needs of the situation. For example, typically, an EMA with a larger stroke length allows for more precise control but loses power (i.e., applies a smaller force). The design of the first actuator **102** allows for a more powerful EMA (with a smaller stroke length) to achieve a larger range of motion of the slider **106** with sufficient power to move the slider **106**.

[0027] The pivot link **122** is coupled between the lever arm **118** and the gearbox **66** to support rotation of the lever arm **118** about the fulcrum point **158**. The pivot link **122** extends between a first link end **162** and a second link end **166**. The first link end **162** is pivotally coupled to a second mounting point **168** on the gearbox **66**. The second mounting point **168** is similar to the first mounting point **146** and includes a pivot bracket with aligned openings, integrally formed in the casing **70** of the gearbox **66**. In other embodiments, the pivot bracket may be otherwise coupled to the gearbox **66**, the bracket may be of another type, and/or the second mounting point **168** may be coupled to another fixed part of the aircraft **10** other than the gearbox **66**. The first link end **162** of the pivot link **122** is pivotally coupled to the second mounting point **168** (e.g., by a pin) to rotatably couple the pivot link **122** to the gearbox **66**. The second link end **166** is pivotally coupled to the fulcrum point **158** of the lever arm **118** (e.g., by a pin) to rotatably mount the lever arm **118** to the pivot link **122**. In the illustrated embodiment, the links in the first actuator **102** are all coplanar, and all of the pivot axes are parallel to each other, and perpendicular to the rotor axis R.

[0028] With reference to FIGS. **3-5**, the cyclic control assembly **98** includes a second actuator **170** and a swashplate assembly **174**. The swashplate assembly **174** is pivotally coupled to the slider **106** and is mounted thereon for translation along the rotor axis R with the slider **106**. The swashplate assembly **174** includes a lower swashplate **178** and an upper swashplate **182** coupled to the lower swashplate **178**. The lower and upper swashplates **178**, **182** are generally annular and include central channels, and are positioned to surround the slider **106** and the main shaft **74**. The lower swashplate **178** is pivotally coupled to the slider **106** (e.g., by a pair of pins) for rotation about a tilt axis **186**. The tilt axis **186** extends perpendicular to and intersects the rotor axis R. In the illustrated embodiment, the tilt axis **186** is parallel to the slider pivot axis **156**, however, in some embodiments the slider pivot axis **156** may be rotated about the rotor axis R with respect to the tilt axis **186**. The upper swashplate **182** is coupled to the lower swashplate **178** to rotate therewith about the tilt axis **186** with respect to the slider **106** and the main shaft **74**. The lower swashplate **178**, also referred to as the stationary swashplate, is a non-rotating component and does not rotate with the main shaft **74** about the rotor axis R. The lower swashplate **178** is fixed to the slider **106** by the second actuator **170** such that the main shaft **74** rotates with respect to the lower swashplate **178**. The upper swashplate **182**, also referred to as the rotating swashplate, is a rotating component and is fixed to rotate with the main shaft **74** about the rotor axis R. The upper swashplate **182** is coupled to the lower swashplate **178** by bearings or bushings allowing rotation therebetween. In the illustrated embodiment, the upper swashplate **182** is driven to co-rotate with the main shaft **74** by a rotating scissor **190** (FIG. **5**). The rotating scissor **190** is illustrated as engaging the main shaft **74** directly, but in other embodiments may engage the rotor hub **82** or other rotating components of the rotor system **42** to transmit rotation to the upper swashplate **182**. The upper swashplate **182** is coupled to the blades **50** of the blade assembly **46** by pitch control rods **90**, which are coupled between anchor points **194** spaced about the upper swashplate **182**. Thus, the upper swashplate **182** is mounted to the lower swashplate **178** to rotate with respect to the lower swashplate **178** and to tilt with the lower swashplate **178** about the tilt axis **186**. Tilting of the swashplate assembly **174** about the tilt axis **186** moves the pitch control rods **90** unevenly and changes the pitch of the blade assembly **46** cyclically, or, in other words, creates a cyclic pitch change of the blade assembly **46**.

[0029] With continued reference to FIGS. **3-5**, the second actuator **170** of the cyclic control assembly is coupled between the swashplate assembly **174** and the slider **106** to control tilting of the swashplate assembly **174** about the tilt axis **186**. The second actuator **170** may also be referred to as the cyclic actuator or the swashplate actuator. The second actuator **170** includes a second link **198** extending between a first end **202** and a second end **206** and including a second EMA **210**. The second EMA **210** can similarly be any type of actuator capable of varying a length thereof such that the second EMA **210** operates similarly to the first EMA **124** and is expandable and retractable to change a length of the second link **198** (i.e., a distance between the first end **202** and the second end **206**). The second EMA **210** may be a similar actuator to the first EMA **124** or may be an actuator of a different type. In the illustrated embodiment, the second EMA **210** includes one or more motors configured to rotate, a transmission that converts rotation from the motor(s) into translation, and an output shaft that translates in response to rotation of the motors. The second EMA **210** and the first EMA **124** may include different properties or characteristics and may each be selected to provide the specific output needed for the respective assembly. For example, in embodiments with a motor and transmission, the EMAs may include different mechanical resolutions (e.g., measured by translation distance per rotation of motor), different electrical resolutions (e.g., measured by degrees of rotation per step/electronic signal input), different output torques, and/or different output speeds. In other embodiments, the EMAs may also have different ranges of translation, different sizes, different weights, etc.

[0030] The first end **202** of the second link **198** is coupled to the slider **106**. In the illustrated embodiment, the first end **202** is pivotally coupled (e.g., by a pin) to a pivot bracket formed in a lower end **214** of a leg bracket **218** of the slider **106**. In the illustrated embodiment, the leg bracket **218** is integrally formed with the slider **106** and extends out and downward from a main portion of the slider **106**. In some embodiments, the leg bracket **218** is otherwise coupled to the slider **106** to translate therewith. The pivotal coupling between the first end **202** and the leg bracket **218** allows the second link **198** to rotate with respect to the slider **106**. The second end **206** of the second link **198** is coupled to the lower swashplate **178** of the swashplate assembly **174**. In the illustrated embodiment, the second end **206** is pivotally coupled to a pivot bracket **220** formed on the lower swashplate **178** to rotatably couple the second link **198** to the swashplate assembly **174**. The pivot bracket **220** is spaced from the tilt axis **186** so that movement of the second end **206** applies a torque that tilts the swashplate assembly **174**.

[0031] Turning to FIG. **5**, the blade assembly **46** is coupled to the forward end **78** of the main shaft **74** for corotation therewith about the rotor axis R to generate the aerodynamic forces applied to the aircraft **10**. The rotor hub **82** is fixed to the forward end **78** of the main shaft **74** and the plurality of blades **50** are circumferentially spaced about the rotor hub **82**. The plurality of blades **50** are spaced evenly and each blade **50** extends from a base end, coupled to the rotor hub **82**, to a distal end **86** along a blade axis B. The blade axis B is sometimes referred to as a feathering axis B. Each blade **50** is supported on the rotor hub **82** for rotation about its respective blade axis B. The blade assembly **46** is illustrated schematically in FIG. **5**, and the specific profiles, relative sizes and dimensions, and 3D configurations (such as twist) of the blades **50** are not limited to those shown in the figures.

[0032] As discussed above, the blade assembly **46** has a variable pitch, and the direction and amount of the force and moment generated by the blade assembly **46** is controlled by the pitch of the blades **50**. Specifically, each blade **50** may have a variable blade pitch and may be rotated about the respective axis B to change the respective blade pitch. The pitch control system **62** is configured to vary the overall pitch of the blade assembly **46** by rotating the blades **50**. Each blade **50** is coupled to the pitch control system **62** by the pitch control rods **90** secured to the blade **50** adjacent the rotor hub **82** and movement of each pitch control rod **90** changes the blade pitch of the connected blade **50**. The pitch control rods **90** are each eccentrically coupled to the respective blade **50** (e.g., connect at a mounting point offset from the blade axis B) so that movement of each pitch control rod **90** along the rotor axis R causes the blade **50** connected thereto to rotate about the blade axis B. The pitch control rods **90** are coupled to anchor points **194** on the upper swashplate **182** to rotate with the upper swashplate **182** about the rotor axis R and match the rotation of the blade assembly **46**. In FIG. **5**, the pitch control rods **90** are schematically shown as coupled to the blade **50** adjacent to the rotor hub **82** and are shown as offset from the blade axis B toward a trailing end **222** of the blade **50**. In other embodiments, the pitch control rods **90** may be coupled to the blade **50** in other locations or in other ways.

[0033] The pitch control system **62** is operable to change the pitch of the blade assembly **46** collectively (i.e., perform a collective pitch change operation) and to change the pitch of the blade assembly **46** cyclically (i.e., perform a cyclical pitch change operation). In the collective pitch change, each of the blades **50** is rotated about its blade axis B by an equal amount such that the blade pitch of each blade **50** is uniformly varied. Specifically, translation of the slider **106** along the rotor axis R translates the control rods **90** simultaneously along the rotor axis R, changing the blade pitch of each blade **50** by a uniform amount. In a cyclic pitch change, each of the blades **50** is rotated about the blade axis B by a different amount based on the respective circumferential position of the blade **50** about the rotor hub **82**, such that the blade pitch of each blade **50** varies differentially. Specifically, tilting the swashplate assembly **174** moves the control rods **90** along the rotor axis R differentially or unevenly, changing the blade pitch of each blade **50** by a different amount.

[0034] In operation, the pitch control system **62** operates the first actuator **102** and the second actuator **170** to vary the pitch of the blade assembly **46** and thereby vary the direction and amount of force and moment provided to the aircraft **10**.

[0035] With reference to FIG. **6**, to perform a collective pitch control operation, the pitch control system **62** operates the collective control assembly **94**, and specifically actuates the first actuator **102**. In one example, the first EMA **124** is actuated to retract and the length of the first link **114** is decreased. In the illustrated embodiment, the actuation may include operating the motor(s) **134** to rotate, converting the rotation to translation through the transmission **138** such that the output shaft **142** is driven to translate (e.g., downward in FIG. **6**). The first end **126** of the first link **114** is coupled to the gearbox **66** so the decrease in length of the first link **114** drives the second end **130** to move the first lever end **150** of the lever arm **118** downward. The lever arm **118** is coupled to the pivot link **122** at the fulcrum point **158**, and movement of the first lever end **150** causes the lever arm **118** to rotate about the fulcrum point **158** so the second lever end **154** moves in a direction generally opposite the direction of the first lever end **150**. The second lever end **154** is coupled to the slider **106** and is therefore constrained to travel in a linear path parallel to the rotor axis R. The pivot link **122** is pivotally coupled to the gearbox **66** such that the fulcrum point **158** is configured to travel along an arced path. Thus, the pivot connections of the gearbox and the pivot link **122** and first link **114** allow for lateral deflection of the lever arm **118** and a lever force transmitted to the slider **106** is applied in the direction of translation of the slider **106** (along the rotor axis R). The movement of the second lever end **154** applies the force to the slider **106** and moves the slider **106** along the rotor axis R toward the blade assembly **46**. Movement of the slider **106** is transmitted to the swashplate assembly **174** via the pivot connection along the tilt axis **186**, and the swashplate assembly **174** is carried with the slider **106** toward the blade assembly **46**. The pitch control rods **90** are therefore also moved toward the blade assembly **46** and rotate the blades **50** about the blade axis B.

[0036] In the illustrated embodiment, expansion of the first EMA **124** causes the trailing end **222** of each blade **50** to lift. In other embodiments, other configurations may be used such that expansion of the first EMA **124** results in a lowering of the trailing end **222**. Depending on the orientation of the aircraft **10** and the swashplate assembly **174**, the blade assembly **46** may generate a force based on the pitch of the blades **50** and the force may provide lift or thrust to the aircraft **10**. The pitch control rods **90** are all moved simultaneously with the slider **106** and each blade **50** is rotated by an equal amount. As the slider **106** translates, the swashplate **174** is carried with the slider **106** by the pinned connection at the tilt axis **186**. The second actuator **170** is also carried with the slider **106** and the swashplate assembly **174**. If the second actuator **170** is not activated, the length of the second link **198** remains unchanged and the translation of the slider **106** is transmitted evenly to the swashplate assembly at the pinned connection and at the pivot bracket **220** where the second actuator **170** connects. Thus, the swashplate assembly **174** does not rotate about the tilt axis **186**. In other words, the cyclic pitch of the blade assembly **46** is maintained with no activation of the second actuator **170**. The second actuator **170** prevents the swashplate assembly **174** from rotating with respect to the slider **106** and maintains the orientation of the swashplate assembly **174** with respect to the blade assembly **46** without being activated or operated.

[0037] The pitch of the blade assembly **46** can thus be collectively adjusted by retracting the first EMA **124**, driving the lever arm **118** to rotate and moving the slider **106** toward the blade assembly **46**, rotating the trailing ends **222** about the blade axis B.

[0038] With reference to FIG. **7**, to perform a cyclic pitch control operation, the pitch control system **62** operates the cyclic control assembly **98**, and specifically the second actuator **170**. In one example, the second EMA **210** expands and the length of the second link **198** is increased. The first end **202** of the second link **198** is coupled to the leg bracket **218**, therefore the expansion of the second EMA **210** causes the second end **206** of the second link **198** to move away from the leg bracket **218**. Movement of the second end **206** drives the swashplate assembly **174** to pivot about the tilt axis **186**. The swashplate assembly **174** is fixed to rotate about the tilt axis **186**, therefore the pivot bracket **220**, and the second end **206** coupled thereto, travels along an arced pathway. The second link **198** pivots with respect to the slider **106** and the swashplate assembly **174** to account for the lateral deflection of the arced pathway. The rotation of the swashplate assembly **174** about the tilt axis **186** is transmitted to the pitch control rods **90** such that the pitch control rods **90** on the side of the swashplate assembly **174** nearer the second actuator **170** are higher than the pitch control rods **90** on the opposite side, and thus the blades **50** are driven to rotate about the respective blade axes B by different amounts so the blades **50** have a different pitch based on the respective position around the rotor hub **82**.

[0039] When the swashplate assembly **174** is in a neutral position, the force generated by the rotor system **42** is generally aligned with the rotor axis R. When the swashplate assembly **174** is tilted about the tilt axis **186** the force generated by the rotor system **42** extends transverse to the rotor axis R. Operation of the cyclic control assembly **98** is independent from operation of the collective control assembly **94**, as the position of the slider **106** along the rotor axis R is not affected by the activation of the second actuator **170**.

[0040] Thus, the pitch control system **62** independently controls the cyclic pitch and the collective pitch of the blade assembly **46** allowing for precise and efficient control of the thrusters **34**. While the pitch control system **62** is described in reference to a rotor system **42** of a convertible aircraft **10**, the pitch control system **62** is equally applicable to thruster and rotor systems on other aircraft requiring precise control and adaptable configurations.

[0041] With reference to FIG. **8**, the pitch control system **62** is coupled to or part of an aircraft control system **300**. The aircraft control system **300** includes a controller **306** that is coupled to pilot interface **310** and sensors **314**. In some embodiments, the aircraft **10** includes a cockpit formed in the body **12** and the pilot interface **310** receives input from the pilot from onboard the aircraft **10**. In some embodiments, the pilot interface **310** is a remote interface that is wirelessly connected to the controller **306** and the pilot wirelessly operates the aircraft control system **300** from a location remote from the aircraft **10**. In some embodiments, the aircraft control system **300** is at least semi-automatic or autonomous and operates without input from a pilot, relying on programmed instructions (e.g., stored in a memory **318**) and input from the sensors **314**. The controller **306** may use the received input from the pilot interface **310** and the sensors **314** in combination with instructions stored in the memory **318** to determine a needed flight control adjustment. For example, sometimes the controller **306** may determine that one or more of the thrusters **34** needs to alter an amount of a generated force or a direction of application of the generated force. The controller **306** sends a control signal **322** to the pitch control system **62**. The control signal **322** may include a first signal instructing the pitch control system to actuate the first actuator **102** (and specifically activate the first EMA **124** to expand or retract) or may include a second signal instructing the pitch control system **62** to actuate the second actuator **170** (and specifically activate the second EMA **210** to expand or retract). Because the first EMA **124** controls collective pitch changes and the second EMA **210** controls cyclic pitch changes, the pitch control system **62** and the overall aircraft control system **300** are able to control the collective and cyclic pitch of the blade assembly **46** separately, and the system does not require mechanical mixing. In some systems, having independent pitch change systems results in less complex signal processing. In some systems, having independent pitch change systems results in independent maintenance and easier identification of needed maintenance and repair. In some systems, having independent pitch change systems allows activation of only one actuator to achieve the needed adjustment without requiring activation of the non-adjusted system simply to maintain the non-adjusted pitch.

[0042] The pitch control system **62** described herein is capable of achieving precise control of the aircraft **10** through the forces generated by the rotor system **42** while maintaining an assembly of minimal complexity that is easy to repair and service. In the illustrated embodiment, the first actuator **102** and the second actuator **170** are positioned on directly opposite sides of the main shaft **74**, and each lie within a plane that intersects the rotor axis R. Thus, the pitch control system **62** has a minimal footprint, allowing the nacelle **38** to be small in size, decreasing drag of the thruster **34**. In other embodiments, the pitch control system **62** may be otherwise arranged to create a desired footprint shape.

[0043] The lever style configuration of the first actuator **102** advantageously allows for precise and quick control of the slider **106**. As discussed above, the fulcrum point **158** of the lever arm **118** can be selected to create a desired mechanical advantage. In some embodiments, the fulcrum point **158** is closer to the first lever end **150** and a small variation in the length of the first link **114** achieves a large translation of the slider **106**. This may allow for rapid changes in the collective pitch of the blade assembly **46**. In some embodiments, the fulcrum point **158** is closer to the second lever end **154** and a large variation in the length of the first link **114** achieves a small translation of the slider **106**. This may allow for precise control of the collective pitch of the blade assembly **46**. The position of the fulcrum point **158** may be selected based on the capability of the first EMA **124** (e.g., the range, the resolution, the torque, the speed, etc.), as well as other factors of the collective control assembly **94**. Additionally, as mentioned above, the configuration of the first actuator **102** allows for lateral deflection of the lever arm **118** during rotation thereof, to allow the second lever end **154** to travel linearly along the rotor axis R. Thus, movement is transmitted through an ‘on-axis’ force applied by the lever arm **118** to the slider **106** along the rotor axis R. This creates a more efficient transmission of power as it decreases or removes any lateral components to the force applied by the lever arm **118** to the slider **106**. Such lateral components may result in higher friction or sticking during movement, decreasing the precision of the pitch control system **62**.

[0044] The pitch control system **62** described herein also offers significant advantages over typical control systems that include mechanical mixing (e.g., using a set of actuators to achieve both collective and cyclic pitch). The collective pitch control and the cyclic pitch control are completely independent, such that operation of the first actuator **102** (including the first EMA **124**) changes the collective pitch of the blade assembly **46** but does not change the cyclic pitch. In other words, the orientation of the swashplate assembly **174**, and therefore the cyclic pitch of the blade assembly **46**, is independent from operation of the first actuator **102**. Specifically, the first EMA **124** can be activated to change the collective pitch and the second EMA **210** can remain inactive during the collective pitch change operation without affecting the cyclic pitch of the blade assembly **46**. This increases the efficiency of the system, because the second EMA **210** does not need to be activated during the collective pitch change operation. The reverse is also true, that the first EMA **124** may remain inactive while the second EMA **210** is activated to change the cyclic pitch without altering the collective pitch. In other words, the position of the slider, and therefore the collective pitch of the blade assembly **46**, is independent from operation of the second actuator **170**. Because the first EMA **124** and second EMA **210** are independent, they can be selected based on specific requirements of the respective systems. For example, the first EMA **124** may be larger and capable of applying more force and varying the length of the first link **114** within a wider range, to be able to apply the needed force to move the slider **106** along the main shaft **74**. The second EMA **210** may be smaller and have a higher resolution to allow more precise control of the tilting of the swashplate assembly **174** and smaller changes in length of the second link **198**. Additionally, the electronic control of the pitch control system **62** is simplified by the use of independent actuators **102**, **170**.

[0045] Embodiments disclosed herein are primarily for exemplary purposes. It should be understood that alternative embodiments or various combinations of features described herein may be implemented.

[0046] Various features and advantages of the embodiments described herein are set forth in the following claims.

Claims

1. An aircraft comprising: a body including a fuselage and a wing assembly; a main shaft supported at the body for rotation with respect to the body about a rotor axis; a blade assembly coupled to the main shaft for corotation therewith, the blade assembly including a rotor hub and a plurality of blades circumferentially spaced about the rotor hub, each blade coupled to the rotor hub for rotation about a respective blade axis; a pitch control system coupled to the blade assembly to rotate each blade about the respective blade axis, the pitch control system including a slider coupled to the main shaft for translation along the rotor axis, wherein translation of the slider rotates each blade about the respective blade axis by an equal amount; a swashplate assembly coupled to the slider for rotation about a tilt axis substantially perpendicular to the rotor axis, wherein rotation of the swashplate assembly about the tilt axis rotates each blade about the respective blade axis by a different amount, a first actuator coupled to the slider, the first actuator including a first link pivotally coupled to the body, a pivot link pivotally coupled to the body and defining a pivot point movable with respect to the body, and a lever arm rotatably coupled to the pivot link for rotation about the pivot point according to movement of the first link, and a second actuator operable to rotate the swashplate assembly with respect to the slider, the second actuator including a second link pivotally coupled to the slider and pivotally coupled to the swashplate assembly; wherein the first link is configured to vary a length thereof to rotate the lever arm about the pivot point and translate the slider along the rotor axis; and wherein the second link is configured to vary a length thereof to rotate the swashplate assembly about the tilt axis.
2. The aircraft of claim 1, wherein the blade assembly is configured to generate a force based on an orientation of each blade about the respective blade axis, and wherein the force may apply lift, thrust, or a combination of lift and thrust to the aircraft.
3. The aircraft of claim 1, wherein the lever arm extends between a first lever end, coupled to the first link, and second lever end, coupled to the slider, and the pivot point is positioned between the first lever end and the second lever end.
4. The aircraft of claim 3, wherein the second lever end travels along a linear path parallel to the rotor axis and the pivot point travels along an arced path.
5. The aircraft of claim 3, wherein the second lever end applies a force to the slider in a direction parallel to the rotor axis.
6. The aircraft of claim 1, wherein the first link includes a first electro-mechanical actuator and wherein the second link includes a second electro-mechanical actuator, and wherein the first electro-mechanical actuator operates independently of the second electro-mechanical actuator.
7. The aircraft of claim 6, wherein an orientation of the swashplate assembly is independent from operation of the first actuator.
8. The aircraft of claim 6, wherein a position of the slider is independent from operation of the second actuator.
9. The aircraft of claim 1, wherein the first link and the pivot link are coupled to a gearbox casing positioned within the body, and wherein the main shaft extends from the gearbox casing along the rotor axis.
10. The aircraft of claim 1, wherein the swashplate assembly includes a lower swashplate and an upper swashplate, wherein the lower swashplate is pivotally coupled to the slider for rotation about the tilt axis.
11. A pitch control system configured to change a pitch of a blade assembly mounted on a main shaft for rotation about a rotor axis, the pitch control system comprising: a slider configured to be coupled to the main shaft for translation along the rotor axis; a slider actuator operable to translate

the slider with respect to the main shaft, wherein the slider actuator is mounted between a fixed body and the slider; a swashplate assembly coupled to the slider for rotation about a tilt axis substantially perpendicular to the rotor axis; and a swashplate actuator operable to rotate the swashplate assembly with respect to the slider, the swashplate actuator mounted between the slider and the swashplate assembly; wherein the slider actuator and the swashplate actuator are independently operated.

12. The pitch control system of claim 11, wherein the slider and the slider actuator are part of a collective control assembly, and wherein the collective control assembly is operable to change the pitch of the blade assembly collectively.

13. The pitch control system of claim 12, wherein the swashplate assembly and the swashplate actuator are part of a cyclic control assembly, and wherein the cyclic control assembly is operable to change the pitch of the blade assembly cyclically.

14. The pitch control system of claim 13, wherein the collective control assembly is operable to vary an amount of the force provided by the blade assembly, and wherein the cyclic control assembly is operable to vary a direction of the force provided by the blade assembly.

15. The pitch control system of claim 11, wherein the swashplate actuator includes an actuator configured to vary a length thereof, and wherein varying the length of the actuator rotates the swashplate assembly about the tilt axis.

16. The pitch control system of claim 15, wherein the actuator is part of a link extending between a first end and a second end, and wherein the first end is coupled to the slider and the second end is coupled to the swashplate assembly.

17. The pitch control system of claim 11, wherein the slider actuator includes a first link coupled to the fixed body, a pivot link coupled to the fixed body and including a pivot point movable with respect to the fixed body, and a lever arm coupled to the first link and the pivot link to rotate about the pivot point.

18. The pitch control system of claim 17, wherein the first link includes an actuator configured to vary a length of the first link and wherein varying the length of the first link rotates the lever arm about the pivot point.

19. The pitch control system of claim 18, wherein rotation of the lever arm about the pivot link applies a force to the slider in a direction parallel to the rotor axis and translates the slider along the rotor axis.

20. An aircraft comprising: a body; a main shaft mounted in the body for rotation about a rotor axis; a blade assembly coupled to an end of the main shaft and configured to provide a force to the body when rotated about the rotor axis, wherein the blade assembly has a pitch that varies and changes the force in response; and a pitch control system according to claim 11, configured to move the blade assembly to change the pitch thereof.