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(54) **FLIGHT CONTROL SYSTEM FOR A HYBRID AIRCRAFT IN THE LIFT AXIS**

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(52) **U.S. Cl.** .... **244/7 R**; 244/7.13; 244/194

(58) **Field of Search** .... 244/6, 7 R, 7 A, 244/17.11, 17.13, 17.19, 17.21, 8, 194, 199

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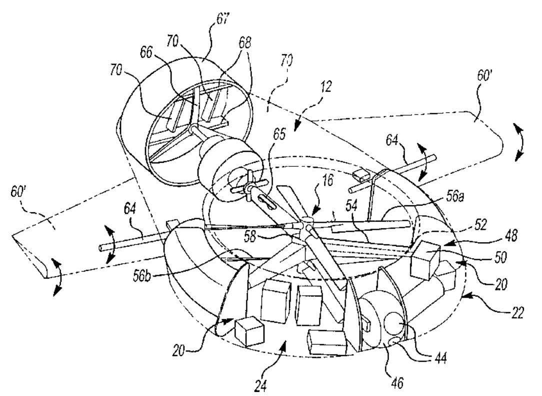
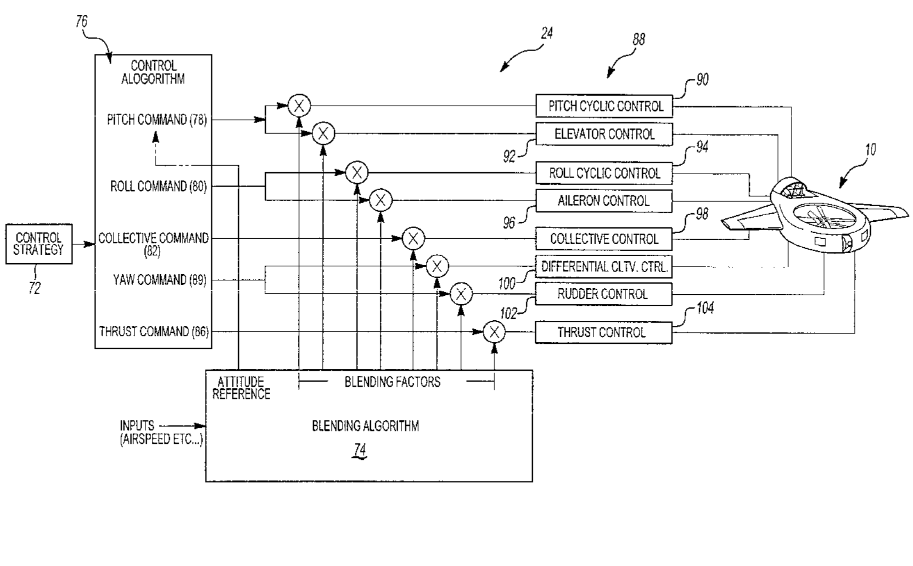
(57) **ABSTRACT**

A flight control system includes a lift control algorithm which selectively communicates with the pitch command of the flight system control algorithm. The lift control algorithm selects the proper control commands to coordinate an effective transition between hover and forward flight. The most efficient vehicle pitch during transition is thereby automatically generated so that sufficient lift and control throughout the transition between rotor borne and wing borne flight.

26 Claims, 7 Drawing Sheets





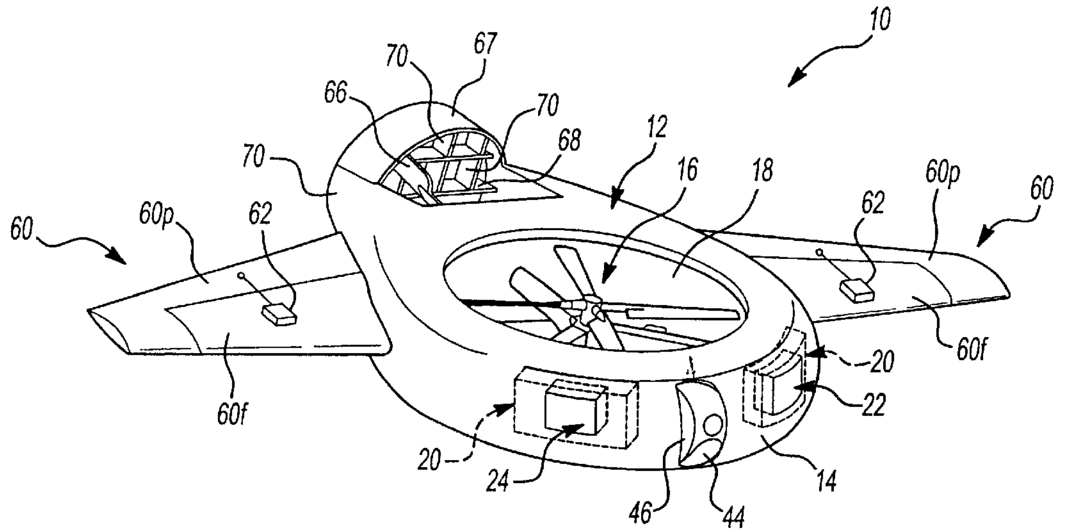

10
70
67
66
70
68
12
70
16
18
60p
60
60
60p
62
62
20
22
60f
60f
20
24
14
46
44

Fig-1

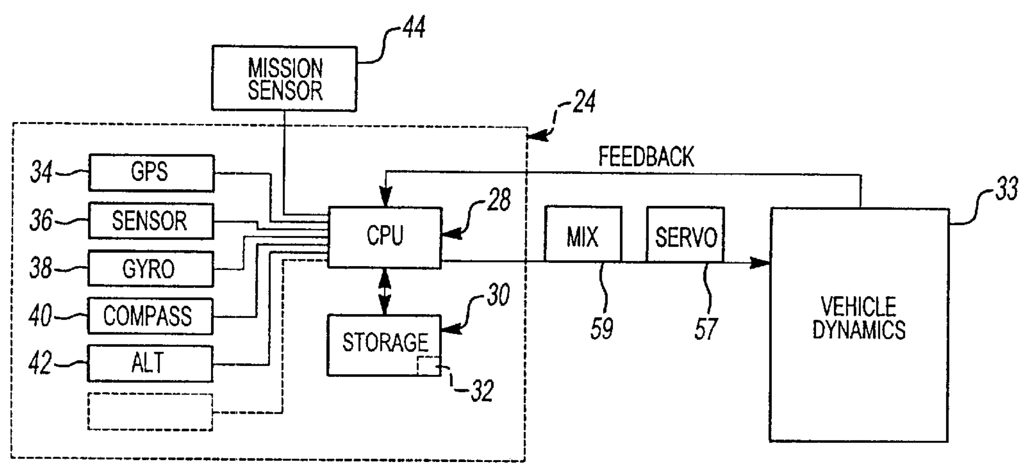

44
MISSION SENSOR
24
FEEDBACK
34
GPS
36
SENSOR
38
GYRO
40
COMPASS
42
ALT
CPU
28
STORAGE
30
32
MIX
SERVO
59
57
33
VEHICLE DYNAMICS

Fig-1A

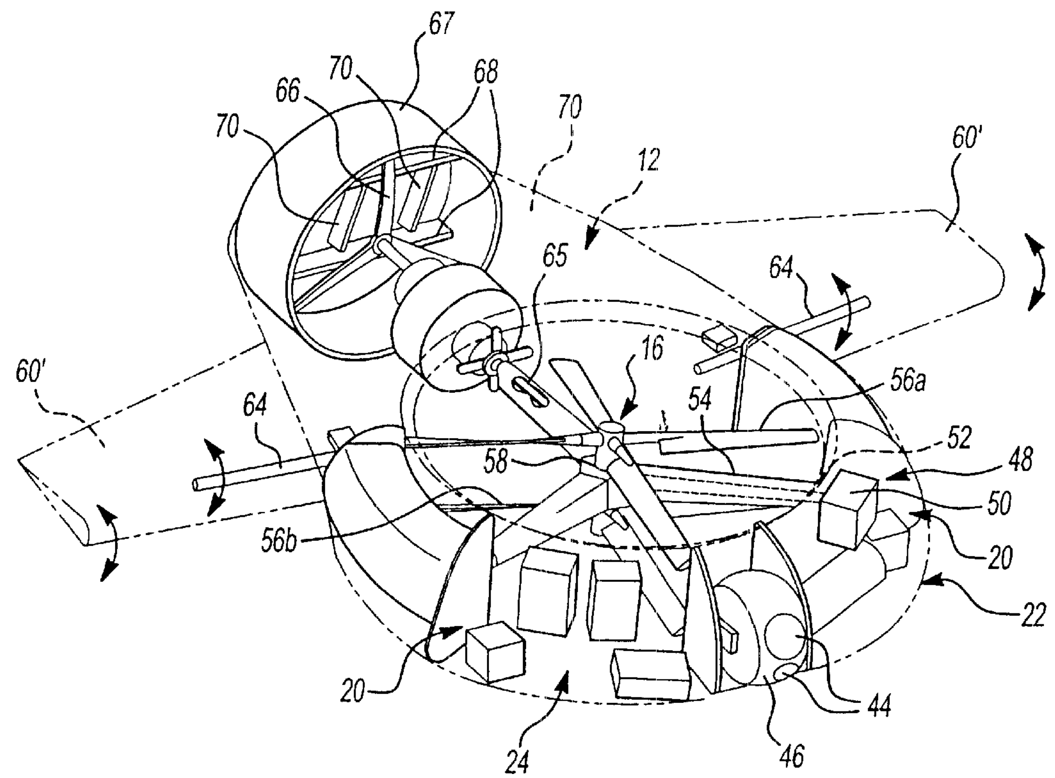

67
70
66
68
70
70
12
60'
65
64
16
56a
60'
64
54
52
58
48
50
56b
20
22
20
44
24
46

Fig-1B

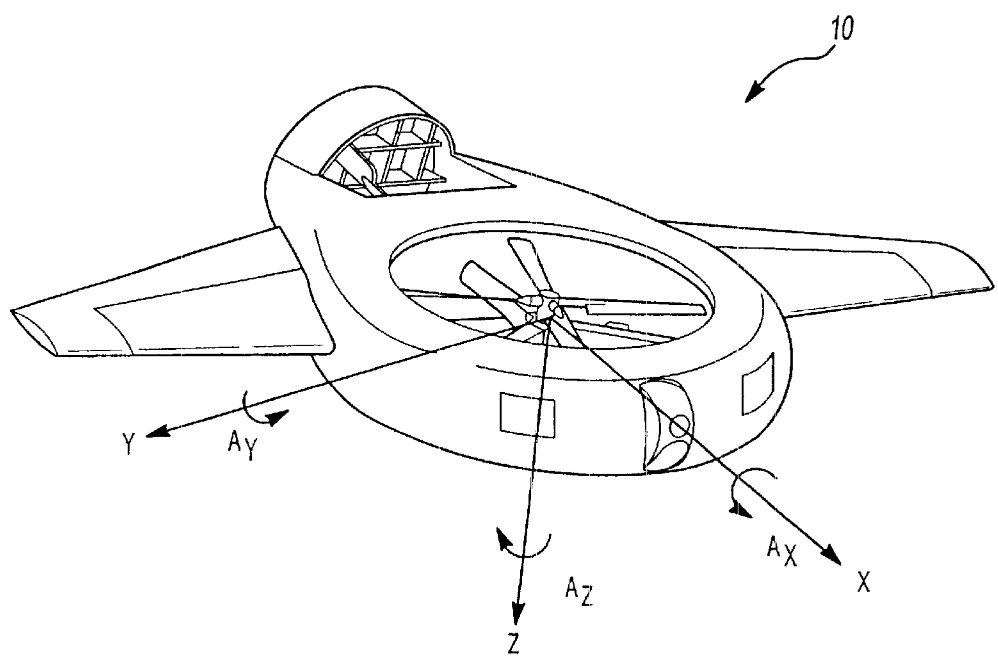

10
Y
AY
AX
X
AZ
Z

Fig-2A

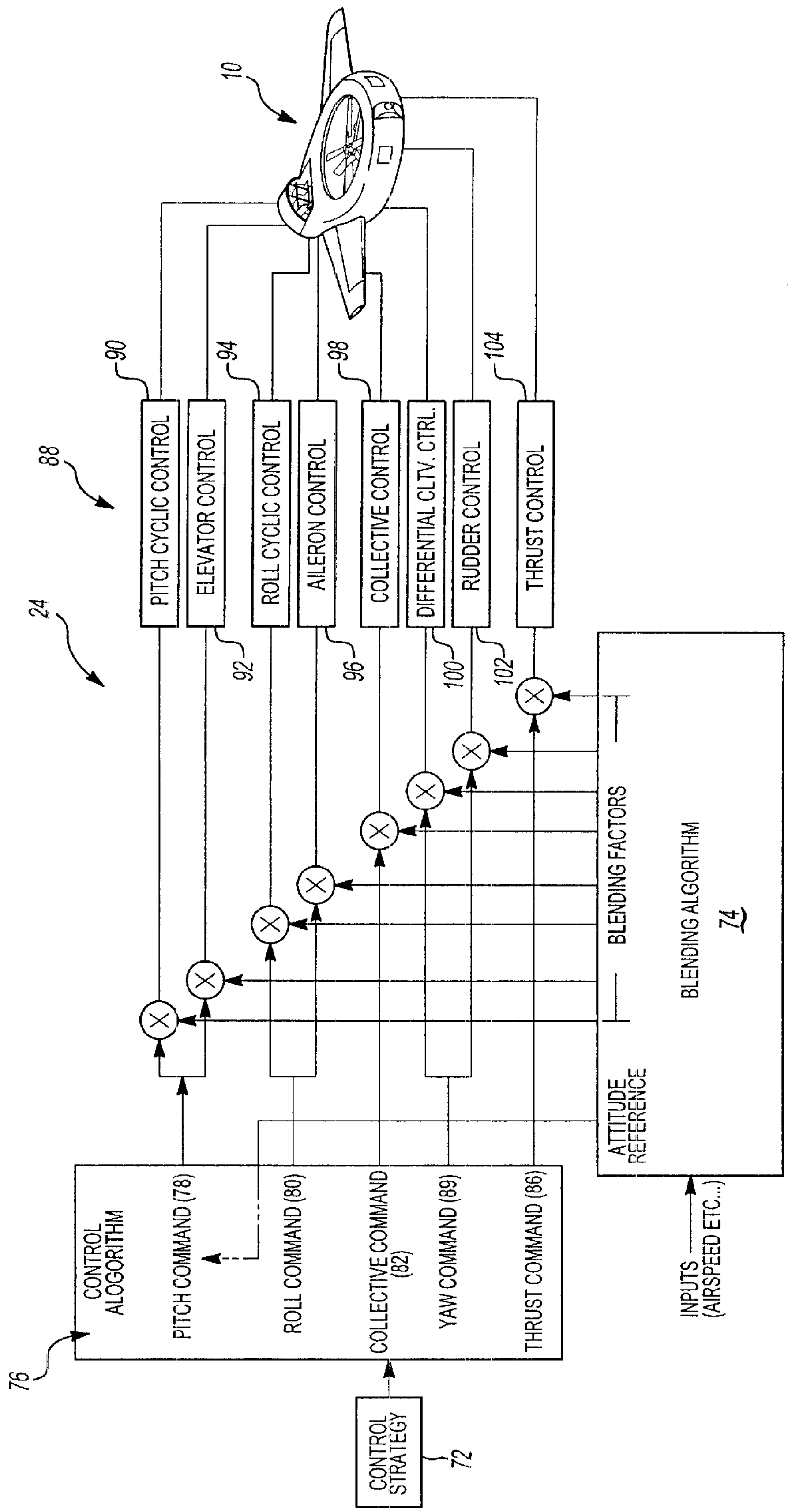

10
88
24
90
92
94
96
98
100
102
104
PITCH CYCLIC CONTROL
ELEVATOR CONTROL
ROLL CYCLIC CONTROL
AILERON CONTROL
COLLECTIVE CONTROL
DIFFERENTIAL CLTV. CTRL.
RUDDER CONTROL
THRUST CONTROL
BLENDING FACTORS
BLENDING ALGORITHM
74
ATTITUDE REFERENCE
INPUTS (AIRSPEED ETC...)
76
CONTROL ALOGORITHM
PITCH COMMAND (78)
ROLL COMMAND (80)
COLLECTIVE COMMAND (82)
YAW COMMAND (89)
THRUST COMMAND (86)
CONTROL STRATEGY
72

Fig-2

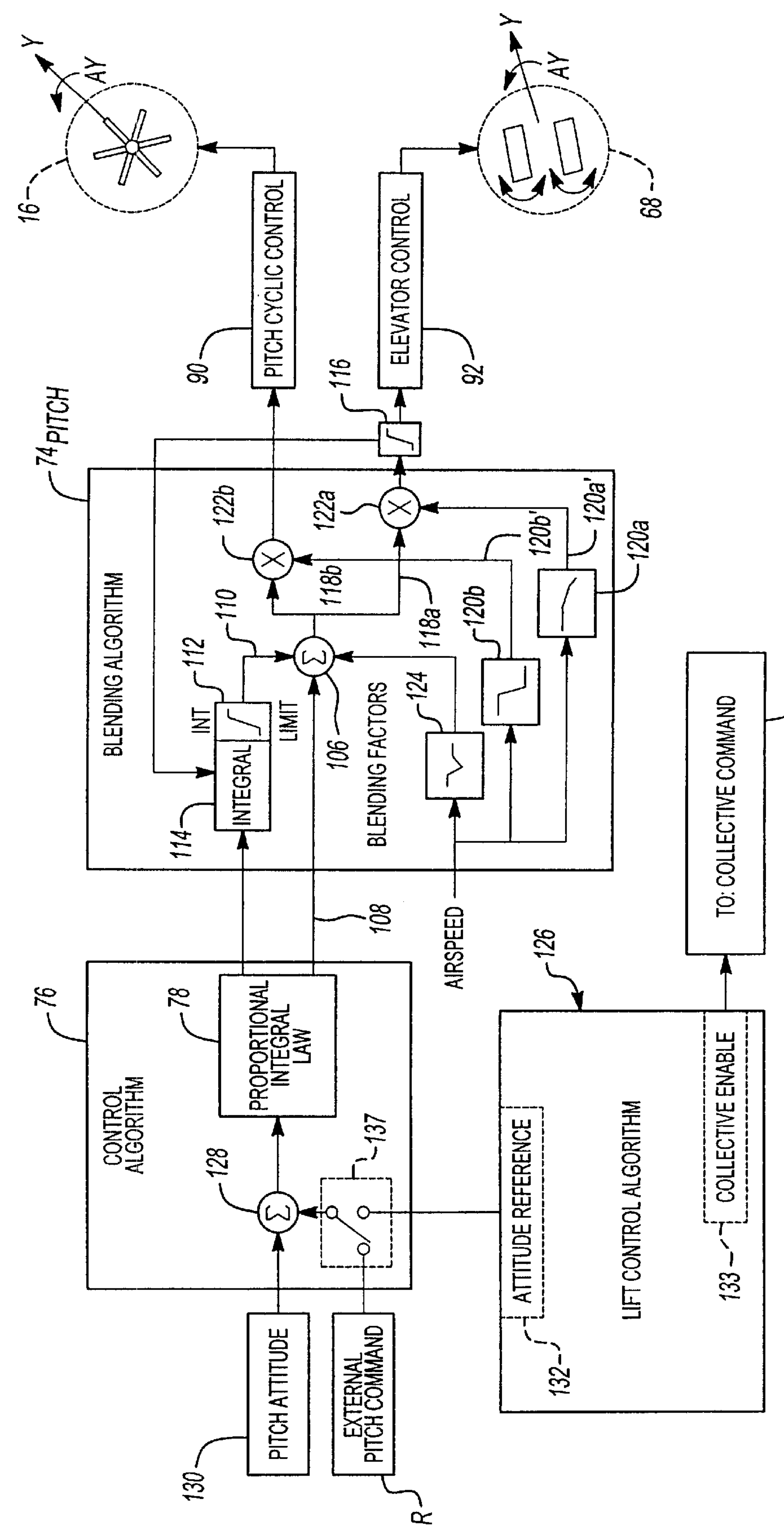
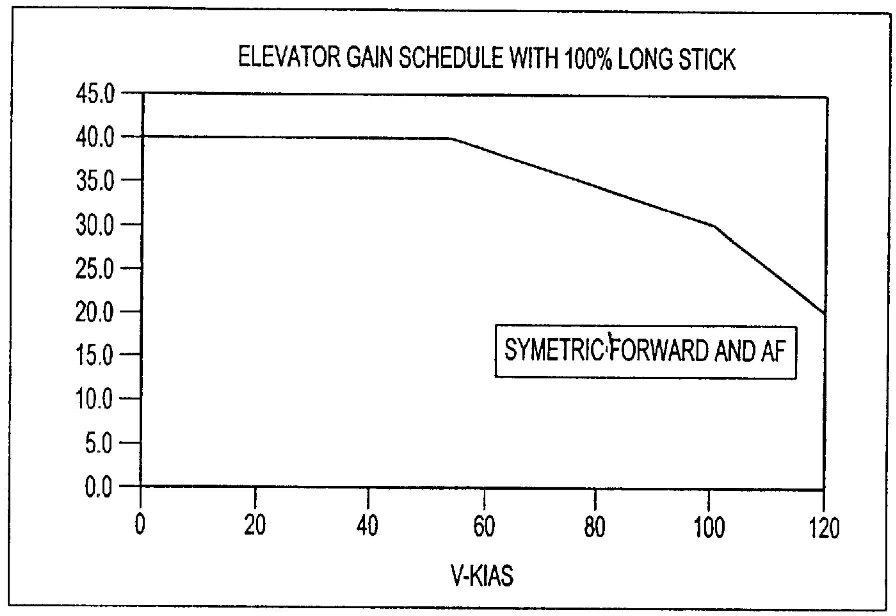

PITCH ATTITUDE
EXTERNAL PITCH COMMAND
CONTROL ALGORITHM
PROPORTIONAL INTEGRAL LAW
BLENDING ALGORITHM
INTEGRAL
INT
LIMIT
BLENDING FACTORS
AIRSPEED
74 PITCH
PITCH CYCLIC CONTROL
ELEVATOR CONTROL
LIFT CONTROL ALGORITHM
ATTITUDE REFERENCE
COLLECTIVE ENABLE
TO: COLLECTIVE COMMAND
Y
AY
16
68
76
78
90
92
82
106
108
110
112
114
116
118a
118b
120a
120a'
120b
120b'
122a
122b
124
126
128
130
132
133
137
R

Fig-3

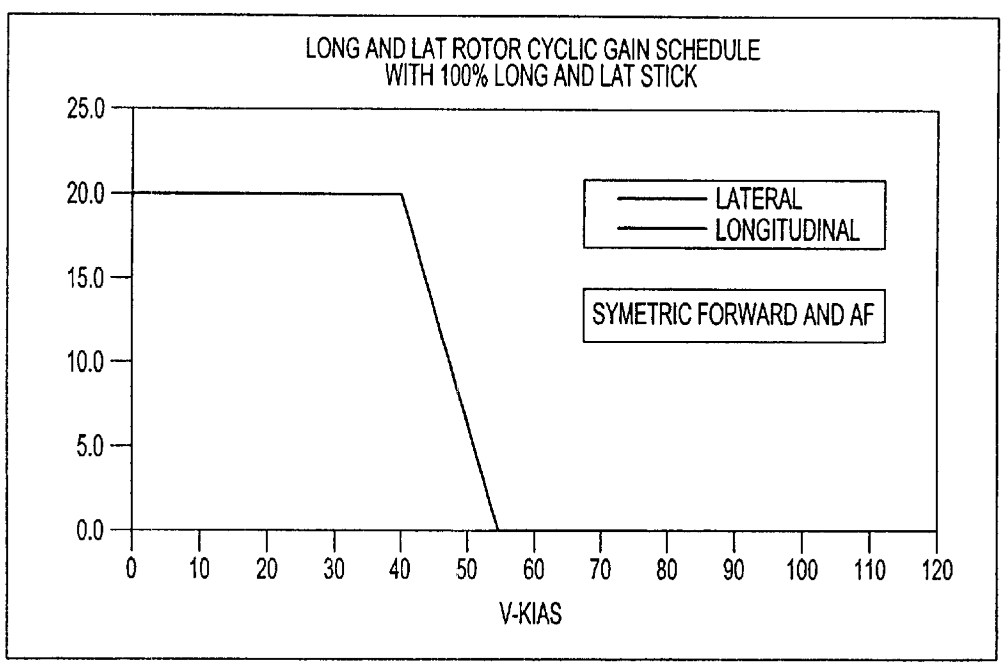
120a



ELEVATOR GAIN SCHEDULE

Fig-4

120b



PITCH CYCLIC GAIN SCHEDULE

Fig-5

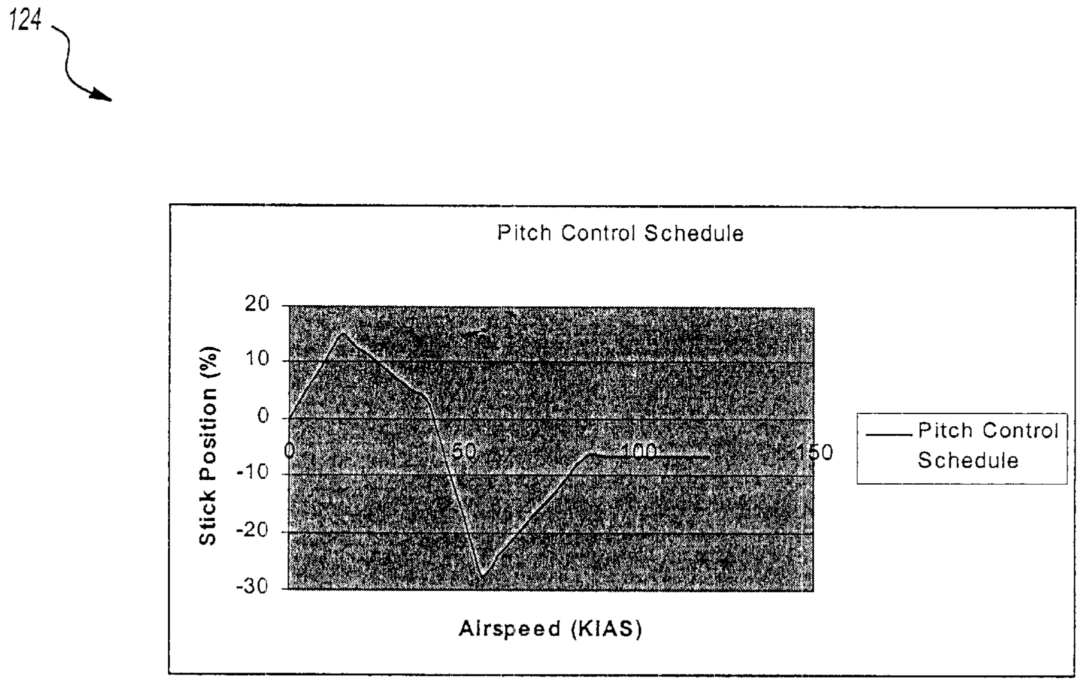

124
Pitch Control Schedule
20
10
0
-10
-20
-30
0
50
100
150
Stick Position (%)
Airspeed (KIAS)
Pitch Control Schedule

Fig-6

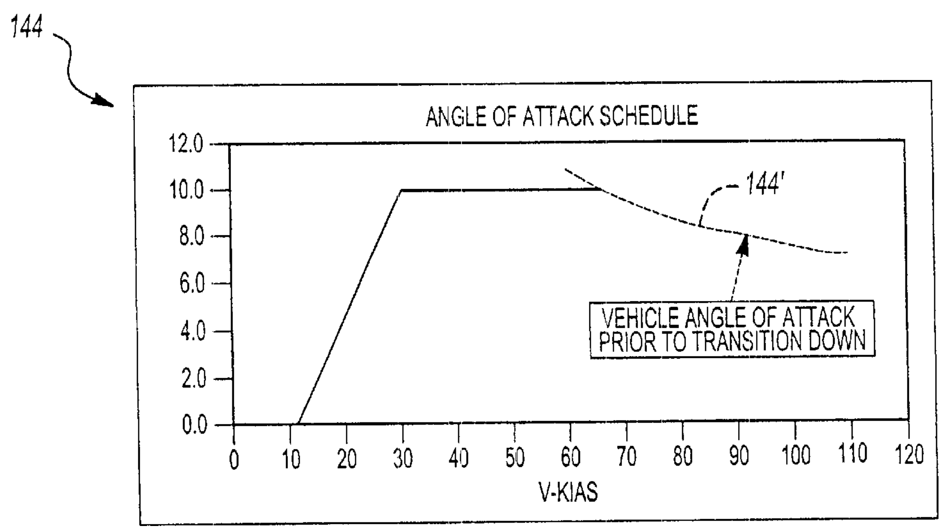

144
ANGLE OF ATTACK SCHEDULE
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
10
20
30
40
50
60
70
80
90
100
110
120
V-KIAS
144'
VEHICLE ANGLE OF ATTACK
PRIOR TO TRANSITION DOWN

Fig-8

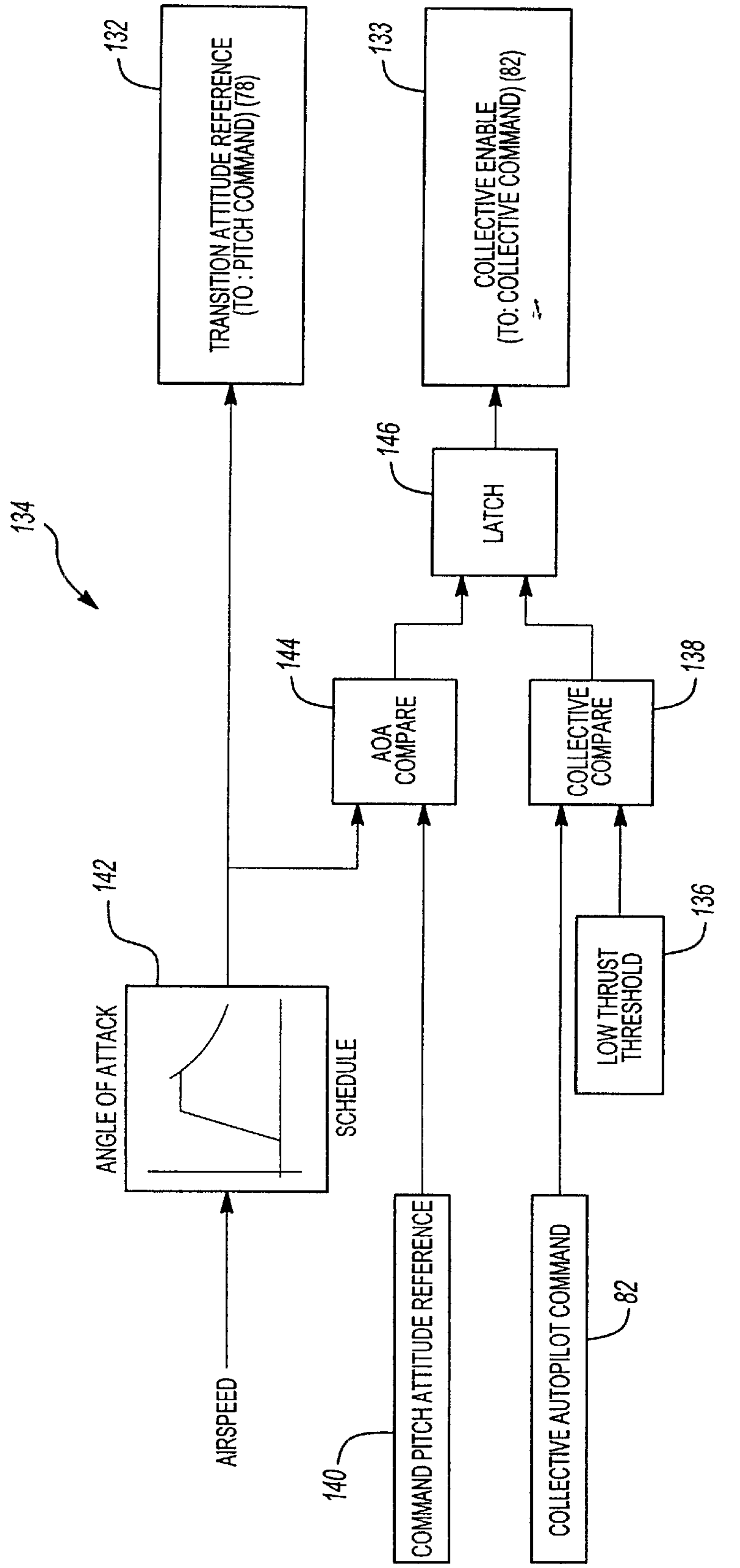

134
132
TRANSITION ATTITUDE REFERENCE
(TO : PITCH COMMAND) (78)
133
COLLECTIVE ENABLE
(TO: COLLECTIVE COMMAND) (82)
146
LATCH
144
AOA
COMPARE
138
COLLECTIVE
COMPARE
142
ANGLE OF ATTACK
SCHEDULE
136
LOW THRUST
THRESHOLD
AIRSPEED
140
COMMAND PITCH ATTITUDE REFERENCE
COLLECTIVE AUTOPILOT COMMAND
82

Fig-7

FLIGHT CONTROL SYSTEM FOR A HYBRID AIRCRAFT IN THE LIFT AXIS

This invention was made with government support under Contract No.: M67854-99C-2081 awarded by the Department of the Army. The government therefore has certain rights in this invention.

BACKGROUND OF THE INVENTION

The present invention relates to a flight control system for a hybrid aircraft, and more particularly, to a flight control system for a hybrid unmanned aerial vehicle (UAV) which blends command signals to a multiple of vehicle control surfaces during transition between rotor borne and wing borne flight.

There is an increased emphasis on the use of UAVs for performing various activities in both civilian and military situations where the use of manned flight vehicles may not be appropriate. Such missions include surveillance, reconnaissance, target acquisition, target designation, data acquisition, communications relay, decoy, jamming, harassment, ordinance delivery, or supply.

A hybrid aircraft provides the hover and low-speed maneuverability of a helicopter with the high-speed forward flight and duration capabilities of a winged aircraft. Typically, hybrid aircraft include a helicopter control surface system which provides cyclic pitch, collective pitch and differential rotation to generate lift, pitch, roll, and roll control when operating in a hover/low-speed environment. Additionally, the hybrid aircraft includes a conventional fixed wing aircraft control surface system such as aileron, elevator, rudder and flaps to provide control when operating in a high-speed environment. Hybrid aircraft also typically include a separate translational propulsive system.

When the hybrid aircraft is operating in a hover/low-speed environment, maneuverability is achieved by controlling the helicopter control system. When the hybrid aircraft is operating in a high-speed environment, the hybrid aircraft operates as a fixed wing aircraft and maneuverability is achieved by controlling the aircraft flight control surfaces. As the hybrid aircraft transitions between helicopter and aircraft control surface systems, however, neither the helicopter nor the aircraft control systems are completely effective. Moreover, the relationship between control displacement and control moment is nonlinear and the aerodynamic forces on the aircraft change most dramatically. Flight control within this region is therefore rather complex.

Accordingly, it is desirable to provide a hybrid aircraft flight control systems which automatically blends command signals to a multiple of vehicle flight control surfaces during transition between rotor borne and wing borne flight. It is further desirable to efficiently control vehicle pitch during transition so that sufficient lift and control throughout the transition is maintained.

SUMMARY OF THE INVENTION

A hybrid aircraft according to the present invention can hover like a helicopter using a rotor system or fly like a fixed wing aircraft using conventional fixed wing controls such that it is operable in four flight regimes:

1. Hover—Defined as low speed operation. The rotor generates control and lift.
2. Forward Flight—Lift is generated by the wings and all control is through the fixed wing surfaces (elevator, ailerons, rudder)

3. Transition Up—This mode guides operation of a multiple of control surfaces when flying from Hover to Forward Flight.
4. Transition Down—This mode guides operation of a multiple of control surfaces when flying from Forward Flight to Hover.

The flight control system according to the present invention includes a lift control algorithm which selectively communicates with the pitch command of the flight system control algorithm. The lift control algorithm controls the pitch attitude of the vehicle when the collective control is enabled and when the vehicle is in transition up/down mode. That is, the lift control algorithm control vehicle pitch during transition between hover and forward flight.

The initial power-up flight mode of the vehicle is Hover. If the vehicle is commanded to fly faster than the transition Up threshold, transition Up mode is entered. During transition Up mode, a transition logic circuit compares the collective command with a low thrust threshold. As vehicle speed increases, the wings create more lift and the flight control law strategy decreases the collective pitch command to maintain a desired vertical control. When the collective pitch command reaches the low thrust threshold, the rotors are maintained at flat collective pitch and are fixed in cyclic pitch. The flight mode is then changed to forward flight mode.

Forward flight mode is maintained so long as the vehicle speed at which the aircraft is commanded to fly exceeds the Transition Down Threshold. It should be understood that the Transition Down threshold is not necessarily the same as the Transition Up threshold. As vehicle speed decreases, the wings generate less lift and the flight control law strategy must increase their angle of attack to maintain desired vertical control. During the Transition down mode, the transition logic circuit compares the commanded pitch attitude reference with an angle of attack schedule. When the commanded pitch attitude reference reaches an angle of attack threshold the collective command is again directed to the collective control such that other than flat pitch is available.

During the transition modes, the lift control algorithm controls the pitch attitude. The lift control algorithm selects the proper control commands to coordinate an effective transition between hover and forward flight. The most efficient vehicle pitch during transition is thereby automatically generated so that sufficient lift and control throughout the transition is maintained. The present invention therefore provides a hybrid aircraft flight control system which automatically control transition between rotor borne and wing borne flight.

BRIEF DESCRIPTION OF THE DRAWINGS

The various features and advantages of this invention will become apparent to those skilled in the art from the following detailed description of the currently preferred embodiment. The drawings that accompany the detailed description can be briefly described as follows:

FIG. **1** is a general perspective view of an exemplary hybrid aircraft having a flight control system according to the present invention;

FIG. **1**A is a block diagram of the flight control system;

FIG. **1**B is a partially phantom view of another exemplary hybrid aircraft having a flight control system according to the present invention;

FIG. **2** is a general schematic block diagram of the flight control law strategy provided by the flight control system of FIG. **2**;

FIG. 2A is a schematic representation of vector axes superimposed on the vehicle of FIG. **1**;

FIG. **3** is a detailed block diagram of one embodiment of a blending algorithm;

FIG. **4** is one embodiment of an exemplary elevator gain schedule for the vehicle of FIG. **1**;

FIG. **5** is one embodiment of an exemplary cyclic pitch gain schedule for the vehicle of FIG. **1**;

FIG. **6** is one embodiment of an exemplary aircraft pitch control gain schedule for the vehicle of FIG. **1**;

FIG. **7** is a detailed block diagram of one embodiment of a transition logic circuit; and

FIG. **8** is one embodiment of an exemplary angle of attack gain schedule for the vehicle of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. **1** illustrates a hybrid aircraft **10**, such as the Unmanned Aerial Vehicle (UAV) developed by Sikorsky Aircraft Corporation. For further understanding of the UAV embodiment and associated components thereof, attention is directed to U.S. patent application Ser. No. 09/296,624 filed Apr. 22, 1999 and entitled "Unmanned Aerial Vehicle With Counter-Rotating Ducted Rotors and Shrouded Pusher-Prop," which is assigned to the assignee of the instant invention and which is hereby incorporated herein in its entirety. It should be further understood that other hybrid aircraft (manned and unmanned) having multiple flight control surfaces will also benefit from the instant invention.

The aircraft **10** includes a fuselage **12** with a toroidal portion **14** having a generally hemi-cylindrical aerodynamic profile. A rotor assembly **16** is mounted within a duct **18** that extends substantially vertically through the fuselage **12**. The fuselage **12** includes a plurality of accessible internal bays **20** for housing and/or storing aircraft flight and mission components. Preferably, the bays house a powerplant system **22** and a flight control system **24**.

The flight control system **24** preferably includes a CPU **28** and storage device **30** connected to the CPU **28** (FIG. 1A). The storage device **30** may include a hard drive, CD ROM, DVD, RAM, ROM or other optically readable storage, magnetic storage or integrated circuit. As will be further described, the storage device **30** contains a database **32** including preprogrammed flight control law strategy associated with a blending algorithm for the control of the vehicle dynamics (illustrated schematically at **33**) through servo actuators and a mixing circuit or the like. The control strategy preferably maintains parameters such as pitch attitude, roll attitude and heading at a desired point to provide control of the vehicle **10**.

The flight control system **24** may alternatively or additionally include a Primary Flight Control System (PFCS) and an Automatic Flight Control Systems (AFCS) as are well known. The AFCS and PFCS software algorithms may be stored in the storage device **30** or alternatively in removable ROM, RAM or flash memory. The AFCS and PFCS provide feedback mechanisms having linear control system logic such as proportional, integral, derivative (PID) paths to achieve the desired response and compensate for undesired destabilization forces acting on the vehicle **10**.

The flight control system further includes transmitters, receivers, navigation, sensors and attitude sensors, such as a GPS receiver **34** and multi-axis accelerometers **36**. The flight control system **24** may alternatively or additionally include one or more gyros **38**, a compass **40**, and an altimeter **42**, all connected to the CPU **28** to detect vehicle dynamics and flight path parameters. The sensors may also include any device capable of outputting an acceleration vector signal representing sensed vehicle motion and/or receiving control surface displacement. Such devices (as well as others) are well known in the aircraft field.

Other mission related sensors **44** (also illustrated in FIG. **1**), such as a camera system, forward looking infrared radar (FLIR) sensor, laser designator, thermal imager, or the like are also preferably located in a trainable turret **46** (FIG. **1**) in a forward area of the vehicle **10**. It should be understood that although a particular component arrangement is disclosed in the illustrated embodiment, other arrangements will benefit from the instant invention.

Referring to FIG. 1B, a drive train assembly **48** is operative for transferring power developed by an engine (illustrated schematically at **50**) to the rotor assembly **16** by a drive shaft **52**. A plurality of hollow struts **54** extend between the fuselage **12** and the rotor assembly **16** to support the rotor assembly **16** therein. The support struts **54** provide structural rigidity to the aircraft duct **18** to prevent flight and ground loads from distorting the fuselage **12** and provide conduits for interconnecting operating elements of the aircraft **10** such as the engine drive shaft **52** and electrical wiring for various operating components.

The rotor assembly **16** includes a pair of multi-bladed, counter-rotating rotors ***56a***, ***56b***, coaxially aligned with the duct **18**, and a coaxial transmission subassembly therebetween (illustrated somewhat schematically at **58**). Each counter-rotating rotor ***56a***, ***56b*** preferably includes a plurality of blade assemblies in which blade pitch changes induced in the counter-rotating rotor systems ***56a***, ***56b***, i.e., cyclic and/or collective pitch inputs, can be utilized to generate lift, pitch, yawl, and roll control of the aircraft **10**. Roll control is preferably provided by roll cyclic of the multi-bladed, counter-rotating rotors ***56a***, ***56b*** through upper and lower swashplates (FIG. 1A, illustrated schematically at **57**) which are controlled through a mixer circuit (FIG. 1A; illustrated schematically at **59**) or the like.

Wings **60** extend laterally outward from the aircraft fuselage **12** to provide high lifting forces and a large nose-down pitching moment in forward translational flight. Those skilled in the art would readily appreciate the diverse wing arrangements that can be incorporated into a UAV according to the present invention. Preferably, each wing **60** includes a fixed stub portion **60**F and a pivotal flight control surface portion **60**P such as a flaperon or aileron. The flight control surface portion **60**P preferably includes a flaperon hingedly mounted to the trailing edge of the wing **60**. A servo actuator **62** mounted within the fixed portion **60**F controls the pivoting of the pivotal portion **60**P (FIG. 1A). Alternatively, or in addition, the entire wing **60**' may pivot such that a drive rod **64** independently changes the angle of attack of the wing **60**' (FIG. 1B).

In order to provide translational thrust, the aircraft **10** includes a pusher prop **66** mounted to the rear of the vehicle **10**. The propeller **66** is mounted to a drive shaft **65** which, in turn, is engaged with the powerplant subsystem through a flexible coupling or the like. The prop **66** is preferably mounted to the rear of the aircraft with its rotational axis oriented substantially horizontal.

A prop shroud **67** is formed on the aft fuselage **70** and around the pusher prop **66**. The cross-sectional shape of the shroud **67** is preferably configured as an airfoil to provide the shroud **68** with some lift component. Mounted on the shroud **68** aft of the pusher prop **66** are one or more horizontal and vertical control surfaces **68**, **70**. Preferably, the control surfaces **68**, **70** are pivotally mounted to the shroud **67** to permit the exhausted air to be channeled in a controllable manner such that the horizontal control surfaces **68** function as elevators and the vertical control surfaces **70** function as rudders.

Referring to FIG. **2**, a block diagram of the inventive flight control system **24** having a flight control law strategy **72** including a control algorithm **76** and a blending algorithm **74** is schematically illustrated. The flight control law strategy **72** provides input to the control algorithm **76** to direct the vehicle **10**. The blending algorithm **74** insures smooth, controllable flight in all flight regimes. This is of particular importance in the transition flight region. Below transition, the aircraft maneuvers like a helicopter utilizing aircraft control surfaces exclusively for control. Above transition, the aircraft maneuvers like a fixed wing airplane utilizing the movable wing portion **60**P exclusively for roll control. Above and below transition, the appropriate control surface is provided with full authority. That is, below transition, the rotor system is movable through its entire control range and above transition, the aircraft control surfaces are movable through their entire control range. During transition, the aircraft uses both the rotor system the aircraft controls surfaced. In this region, the relationship between control displacement and control moment is most nonlinear. Transition is also the region where the aerodynamic forces on the aircraft change most dramatically. The blending algorithm compensates for these effects and thereby improves control.

The flight control strategy **72** includes a control algorithm **76** to output a pitch command **78**, a roll command **80**, a collective command **82**, a yaw command **84** and a thrust command **86**. The flight control commands **78–86** are generated by manual input from a remote operator, the flight control system **24** or a combination thereof.

Orthogonal vector axes superimposed on the vehicle **10** (FIG. **2**A) illustrate that the pitch command **78** provides angular moment about the Y axis (Ay); the roll command **80** provides angular moment about the X axis (Ax); the collective command **82** provide translational moment along the Z axis; the yaw command **84** provides angular moment about the Z axis (Az); and the thrust command **86** provides translation moment about the X axis. It should be understood that numerous hybrid aircraft flight control systems will benefit from the blending algorithm of the instant invention.

The flight control commands **78–86** are output to a multiple of movable control surfaces **88** to achieve the desired moment about the desired axis or axes. In the disclosed embodiment, the movable control surfaces **88** include a pitch cyclic control **90**, elevator control **92**, roll cyclic control **94**, aileron control **96**, collective control **98**, differential collective control **100**, rudder control **102**, and thrust control **104**.

Each flight control command **78–86** is output to one or more movable control surfaces **90–104** to control the vehicle in a particular axis. The control commands **78–86** are actuating commands which are sent to a servo actuator, a mixing circuit for a plurality of servos which control the swashplates (FIG. **3**) or the like which are suitably arranged to control the rotor blades and/or otherwise adjust the deflection of a movable control surface. Preferably, one of the control surfaces **90–104** is primarily a helicopter flight control surface, while the other is primarily a conventional aircraft flight control surface.

In the disclosed embodiment, the pitch command **78** is associated with the pitch cyclic control **90** and the elevator control **92**; the roll command **80** is associated with the roll cyclic control **94**, and the aileron control **96**; the collective command **82** is associated with the collective control **98**; the yaw command **84** is associated with the differential collective control **100** and the rudder control **102**; and the thrust command **86** is associated with the thrust control **104** (FIGS. **1**A and **1**B; pusher prop **66**). Although particular control surfaces are disclosed in the illustrated embodiment, it should be understood that other combinations of movable control surfaces, and other types of controls such as slats, flaps, flaperons, puffer ducts, articulatable nozzles, elevons, and the like will also benefit from the instant invention. It should be further understood that the term aileron is defined to include conventional ailerons, flaperons, elevons and other controls which provide a pitch moment other than rotor-type cyclic controls.

Referring to FIG. **3**, the blending algorithm **74** in the pitch axis (**74**pitch) is schematically illustrated. The roll blending algorithm **74**pitch is preferably operable when the vehicle is in the transition flight region.

Pitch summing circuit **106** receives the pitch command input **78** (also shown in FIG. **2**) preferably in proportional plus integral form. The proportional and integral commands are the primary control commands and are computed by the underlying control laws within the flight control strategy **72**. That is, a proportional pitch command **108** is summed with an integral pitch command **110** which has been limited by a limiting circuit **112**.

As generally known, limiting circuits prevent a signal from exceeding a certain specified magnitude or dropping below a certain magnitude thereby providing authority limits. Limit **112** controls the rate of the output of the pitch integrator **114**. Pitch integrator unit **114** is used to maintain a desired pitch cyclic control **90** and/or elevator control **92** without the necessity of constant displacement of the pitch command **78**. It should be understood that commands may alternatively or additionally be split with other flight control surfaces such as the flaperons **60**P (FIG. **1**A). The limiting circuit **112** preferably prevents the pitch integrator **114** from greatly exceeding a predetermined limit commonly known as "integrator wind-up." To further assure that the pitch integrator **114** does not exceed the maximum travel of the elevator **68**, a second limiter **116** is provided in a feed back path. If limiter **116** is reached, limited **116** assists the limit **112** to assure the pitch integrator **114** is held in the limited direction thereby preventing exceeding control surface mechanical limits and integrator wind-up.

From the pitch summing circuit **106**, the pitch command **78** is split into separate command paths **118*a*** and **118*h***. Each command path **118*a***, **118*h*** is respectively multiplied by an elevator gain **120*a*'** and a pitch cyclic gain **120*h*'** at multipliers **122*a***, **122*h***. The elevator gain **120*a*'** is determined by an elevator gain schedule **120*a*** (FIG. **4**) which relates the velocity (air speed) of the vehicle **10** to allowable elevator control **92** deflection. The pitch cyclic gain **120*h*'** is determined by a pitch cyclic gain schedule **120*h*** (FIG. **5**) which relates the velocity (air speed) of the vehicle **10** to the allowable cyclic deflection for the pitch axis. The gain schedules are preferably quantitative measures of control effectiveness.

Based upon the respective gain schedule **120**A, **120*h***, the pitch blending algorithm **74**pitch determines how much of the pitch input command **78** is sent to each movable control surface (through the pitch cyclic control **90** and/or elevator control **92**.)

For example only, in the illustrated embodiment, no pitch cyclic deflection is available when the velocity of the vehicle

10 exceeds 55 kias. If, for example, the vehicle **10** is travelling at a velocity of 100 kias, the entire pitch command **78** is sent to the elevator (pitch cyclic gain **120***h*'=0). The elevator deflection is also reduced from its full deflection to about 39 degrees. The decreasing elevator deflection limit accounts for increased vehicle velocity and increased elevator control effectiveness. Preferably, the gain schedules **120***a*, **120***h* are determined so that for any given control command, the same amount of vehicle moment will be generated regardless of flight regime. That is, the gain schedules assure that the vehicle responds in a substantially identical manner independent of it velocity. This simplifies the underlying flight control system laws since the command the flight control system generates provide the desired moment regardless of flight regime.

Preferably, the blending algorithm **74**pitch manages control limits so that if one control surface is at its maximum limit of travel, the other control surface assists the saturated control surface. That is, the pitch blending algorithm **74**pitch adds in additional elevator control authority if the pitch cyclic is at its maximum deflection even if the additional elevator control authority may not be effective. This minimizes the possibility of entering uncontrolled flight due to unavailable control authority.

The main limit is that of the pitch integrator **114**. When the pitch cyclic control **90** reaches its full deflection (full saturation), elevator control **92** is added in by the flight control system **24**. For example only, if the vehicle is traveling forward at a relatively low velocity, and a large pitch input command **78** is provided, pitch cyclic control **90** may not provide the necessary control authority commanded by the flight control system **24**. The blending algorithm **74**pitch preferably responds by maintaining the pitch cyclic control **90** at full deflection while adding in elevator control **92** to achieve the desired response.

An aircraft pitch control gain schedule **124** (also illustrated in FIG. **6**) is also added to the pitch command **78** at the pitch summing circuit **106**. The pitch control schedule **124** provides a feed forward pitch control signal which provides a predetermined hold or trim to the movable control surface (pitch cyclic control **90** and/or elevator control **92**) to compensate for shifts in the trim positions caused by airspeed relative aerodynamic conditions. For example only, airflow adjacent the duct has a predetermined effect upon the pitch of the vehicle **10** relative to airspeed. A particular nose-up pitch effect at a particular airspeed is thereby accounted for by a nose-down pitch trim in the pitch control schedule **124**.

A lift control algorithm **126** selectively communicates with the pitch command **78** of the control algorithm **76** through a pitch summing circuit **128**. The lift control algorithm **126** controls the pitch attitude of the vehicle **10** when the collective control **98** (FIG. **2**) is enabled and when the vehicle is in transition up/down mode. That is, the lift control algorithm **126** control vehicle pitch during transition between hover and forward flight.

Lift summing circuit **128** receives a pitch attitude **130** from the flight control law strategy **72** (FIG. **2**) to generate a pitch attitude error. It should be understood that the pitch attitude error is used as an input to the pitch command **78** of the flight control law strategy **72** control algorithm **76** to adjust vehicle pitch attitude. An external manual pitch command from a remote operator (illustrated schematically at R) or the lift control algorithm **126** is selectively provided to the pitch command **78** through the lift summing circuit **128**. A lift control enable switch (illustrated schematically at **132**) determines which communicates with the lift summing circuit **128** to provide the pitch attitude reference to the pitch command **78**. The lift control algorithm **126** also operates a collective enable switch **133**. The collective enable switch **133** operates to freeze the collective command **80** at a particular position, e.g., flat pitch at in forward flight mode.

Referring to FIG. **7**, a transition logic circuit **134** which operates the lift control enable switch **133** and the collective enable switch **132** is schematically illustrated. The transition logic circuit **134** determines vehicle operation within each flight mode and determines when to switch flight modes. The flight modes are:

1. Hover—Defined as low speed operation. The rotor generates control and lift.
2. Forward Flight—Lift is generated by the wings and all control is through the fixed wing surfaces (elevator, ailerons, rudder.)
3. Transition Up—This mode guides operation of a multiple of control surfaces when flying from Hover to Forward Flight.
4. Transition Down—This mode guides operation of a multiple of control surfaces when flying from Forward Flight to Hover.

The initial power-up flight mode of the vehicle **10** is Hover. The rotor generates control and lift. Pitch command **78** is generated by the remote operator R and/or the flight control law strategy **72**. So long as the airspeed of the aircraft does not exceed the Transition Up threshold, the aircraft will remain in Hover mode. If the vehicle **10** is commanded to fly faster than the Transition Up threshold, Transition Up mode is entered. During this mode the aircraft is accelerating toward forward flight speed. During the transition Up mode, the transition logic circuit **134** compares the collective command **82** (also illustrated in FIG. **2**) with a low thrust threshold **136** at a collective comparator **138**. The low thrust threshold **136** is preferably defined as 0 degrees collective (flat pitch of rotor blades.)

As vehicle speed increases, the wings **60** (FIGS. **1**A and **1**B) create more lift and the flight control law strategy **72** must decrease the collective pitch command **82** (FIG. **2**) to maintain the desired vertical control. When the collective pitch command **82** reaches the low thrust threshold **136**, the transition logic circuit **134** toggles the latch **146** to hold the collective pitch command **82** at the low thrust threshold **136** and also sets all further cyclic controls (pitch **90** and roll **94**; FIG. **2**) to zero. That is, the rotors **56***a*, **56***b* (FIG. **1**B) be maintained at flat collective pitch and are fixed in cyclic pitch. The flight mode is then changed to forward flight control of the pitch command **78** is returned to the remote operator R and/or the flight control law strategy **72**. Thus, although the flight control law strategy **72** may generate appropriate pitch cyclic commands **90** and roll cyclic commands **94**, the transition logic circuit **136** prevents those commands from being sent to the swashplates **57** (FIG. **1**A) such that flat pitch and the resultant aerodynamic duct cover is maintained.

During Transition Up mode when the collective command **82** is enabled, the lift control algorithm **126** (FIG. **3**) controls the pitch attitude. That is, the lift control enable switch **137** (FIG. **3**) is switched such that the lift control algorithm **126** communicates with the lift summing circuit **128** to provide the transition pitch attitude reference **132** to the pitch command **78**. The lift control algorithm **126** selects the proper control commands to affect an effective transition. The most efficient vehicle pitch during Transition Up is thereby automatically generated so that sufficient lift and control throughout the transition is maintained.

Forward flight mode is maintained so long as the vehicle speed at which the aircraft is commanded to fly exceeds the Transition Down Threshold. It should be understood that the Transition Down threshold is not necessarily the same as the Transition Up threshold.

If the vehicle **10** is commanded to fly slower than the Transition Down threshold, Transition Down mode is entered. As vehicle speed decreases, the wings **60** generate less lift and the flight control law strategy **72** must increase their angle of attack to maintain desired vertical control. During the Transition Down mode, the transition logic circuit **134** compares the commanded pitch attitude reference **140** (angle of attack) with an angle of attack schedule **142** (FIG. **8**) at an angle of attack comparator **144**. The source of the commanded pitch attitude reference **140** is preferably the external pitch command R (FIG. **3**) and/or the flight control law strategy **72** (FIG. **2**). When the commanded pitch attitude reference **140** reaches an angle of attack threshold **144**' (FIG. **8**), the transition logic circuit **134** toggles the latch **146** enables the collective command **82** to resume control. That is, the collective command **82** is again directed to the collective control **98** such that other than flat pitch is available.

The angle of attack schedule **144** (FIG. **8**; solid line) provide a predetermined relationship between pitch attitude and velocity of the vehicle **10**. For example only, and as illustration FIG. **8**, as the vehicle reduces velocity, its pitch attitude increases (angle of attack—dashed line) until its pitch attitude (dashed line) crosses the angle of attack schedule (solid line) at 68 kias and 10 degrees. It should be understood that the lines may cross and Transition Down mode entered anywhere along the angle of attack schedule **144**.

During Transition Down mode when the collective command **82** is enabled, the lift control algorithm **126** (FIG. **3**) controls the pitch attitude. That is, the lift control enable switch **137** (FIG. **3**) is switched such that the lift control algorithm **126** communicates with the lift summing circuit **128** to provide the transition pitch attitude reference **132** to the pitch command **78**. The lift control algorithm **126** selects the proper control commands to affect an effective transition. The most efficient vehicle pitch during Transition Down is thereby automatically generated so that sufficient lift and control throughout the transition is maintained.

Once the vehicle speed is reduced to a predetermined hover speed, Hover mode is again entered. Control of the pitch command **78** is returned to the remote operator R and/or the flight control law strategy **72**.

Furthermore, while it is understood it still is worth stating that the present invention is not limited to a microprocessor based control system. The system may be implemented in a non-microprocessor based electronic system (either digital or analog).

The foregoing description is exemplary rather than defined by the limitations within. Many modifications and variations of the present invention are possible in light of the above teachings. The preferred embodiments of this invention have been disclosed, however, one of ordinary skill in the art would recognize that certain modifications would come within the scope of this invention. It is, therefore, to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described. For that reason the following claims should be studied to determine the true scope and content of this invention.

What is claimed is:

1. A flight control system for a hybrid aircraft comprising:

a movable first control surface operable to direct an aircraft about a pitch axis, said first control surface not on a rotor system;

a movable second control surface operable to direct the aircraft about said pitch axis, said second control surface on a rotor system which rotates throughout a hover flight mode, a transition up flight mode, a forward flight mode and a transition down flight mode;

a storage device having a blending algorithm and a lift control algorithm, said blending algorithm determining a first gain for said first control surface according to a first gain schedule, and determining a second gain for said second control surface according to a second gain schedule in response to a control input for said pitch axis; and

a controller in communication with said first control surface, said second control surface, and said storage device, said controller operable to receive a control command for said pitch axis and actuate said first control surface according to said first gain and said second control surface according to said second gain, said lift control algorithm selectively operable to generate said control command during transition between a hover flight mode and a forward flight mode.

2. The flight control system as recited in claim **1**, wherein said first gain schedule and said second gain schedule relate control surface deflection to aircraft airspeed.

3. The flight control system as recited in claim **1**, wherein said first control surface includes an elevator.

4. The flight control system as recited in claim **3**, wherein said first control surface includes a flaperon.

5. The flight control system as recited in claim **1**, wherein said second control surface comprises a swashplate to effect a pitch cyclic change in said rotor system.

6. The flight control system as recited in claim **5**, wherein said rotor system includes a coaxial counter rotating rotor system mounted within a duct.

7. The flight control system as recited in claim **1**, wherein said hybrid aircraft is an unmanned aerial aircraft.

8. The flight control system as recited in claim **1**, wherein said lift control algorithm is selectively operable in response to a low thrust threshold.

9. The flight control system as recited in claim **8**, wherein said low thrust threshold comprises a predetermined collective pitch of said rotor system to cater transition up flight mode.

10. The flight control system as recited in claim **1**, wherein said first gain and said second gain comprise quantitive measures of control effectiveness.

11. The flight control system as recited in claim **1**, wherein said blending algorithm increases control authority of said movable first control surface when said movable second control surface becomes saturated.

12. The flight control system as recited in claim **1**, wherein said lift control algorithm compares a commanded pitch attitude reference with an angle of attack schedule to enter said transition down flight mode.

13. A method of controlling a hybrid aircraft comprising the steps of:

(1) determining whether the hybrid aircraft is within a transition flight mode; and

(2) generating a pitch control command for a pitch aircraft axis by a lift control algorithm in response to said step (1), said pitch control command comprising a first gain

for a first control surface according to a first gain schedule, said first control surface not on a rotor system, and said pitch control command comprising a second gain for a second control surface according to a second gain schedule, said second control surface on a rotor system which rotates throughout a hover flight mode, a transition up flight mode, a forward flight mode and a transition down flight mode.

14. A method as recited in claim **13**, further comprising the steps of:

(1a) receiving a collective pitch command;

(1b) comparing the collective pitch command of said step (1a) with a low thrust threshold; and

(1c) generating said control command for said pitch aircraft axis by said lift control algorithm in response to said step (1b).

15. A method as recited in claim **14**, wherein said step (1c) includes entering into a transition up flight mode.

16. A method as recited in claim **15**, wherein said step (1c) includes maintaining a flat collective pitch upon exiting the transition up flight regime into a forward flight mode.

17. A method as recited in claim **15**, wherein said step (1c) includes preventing cyclic pitch commands upon exiting said transition up flight regime into a forward flight mode.

18. A method as recited in claim **14**, wherein said low thrust threshold of said step (1b) is a flat collective pitch.

19. A method as recited in claim **14**, further comprising the steps of:

(1a) receiving a pitch attitude reference;

(1b) comparing the pitch attitude reference of said step (1a) with an angle of attack schedule; and

(1c) generating said control command for said pitch aircraft axis by said lift control algorithm in response to said step (1b).

20. A method as recited in claim **19**, wherein said step (1c) includes entering into a transition down flight mode.

21. A method as recited in claim **19**, wherein said step (1c) includes maintaining a flat collective pitch upon exiting the transition up flight regime into a forward flight mode.

22. A method as recited in claim **19**, wherein said angle of attack schedule includes a predetermined relationship between aircraft airspeed and aircraft pitch attitude.

23. A method as recited in claim **19**, wherein said step (1c) includes enabling collective pitch control upon entering a transition down flight regime.

24. A method as recited in claim **14**, wherein said step (2) includes disengaging the lift control algorithm during a forward flight mode and a hover mode.

25. A method as recited in claim said **19**, step (1c) comprises enabling collective pitch control when the pitch attitude reference of said step (1a) crosses the angle of attack schedule defined by a predetermined relationship between aircraft airspeed and aircraft pitch attitude.

26. A method as recited in claim **19**, wherein said step (1c) comprises entering the transition down flight mode when the pitch attitude reference of said step (1a) crosses the angle of attack schedule defined by a predetermined relationship between aircraft airspeed and aircraft pitch attitude.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,592,071 B2 Page 1 of 1
DATED : July 15, 2003
INVENTOR(S) : W. Douglas Kinkead et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 10,
Line 48, "cater" should be -- enter --

Signed and Sealed this

Second Day of December, 2003

JAMES E. ROGAN
Director of the United States Patent and Trademark Office