



US006170778B1

(12) **United States Patent**
Cycon et al.

(10) **Patent No.:** **US 6,170,778 B1**
(45) **Date of Patent:** **Jan. 9, 2001**

- (54) **METHOD OF REDUCING A NOSE-UP PITCHING MOMENT ON A DUCTED UNMANNED AERIAL VEHICLE**
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- (73) Assignee: **Sikorsky Aircraft Corporation**, Stratford, CT (US)
- (*) Notice: Under 35 U.S.C. 154(b), the term of this patent shall be extended for 0 days.

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- (21) Appl. No.: **09/296,716**
- (22) Filed: **Apr. 22, 1999**
- (51) **Int. Cl.⁷** **B64C 27/30**
- (52) **U.S. Cl.** **244/6; 244/12.3; 244/23 B**
- (58) **Field of Search** **244/17.11, 23 B, 244/12.3, 6, 7 R, 7 A, 7 B**

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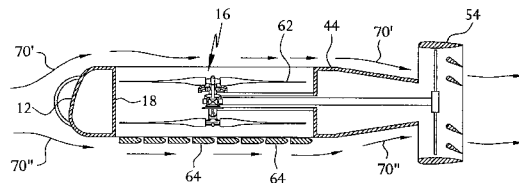
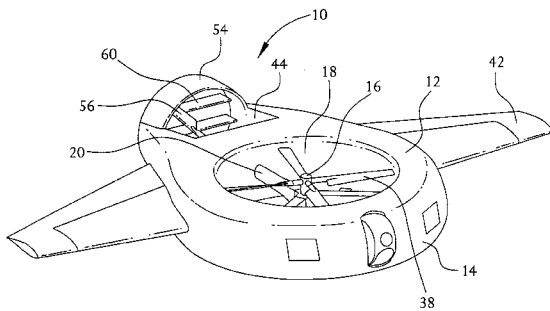
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(57) **ABSTRACT**

A method for reducing a nose-up pitching moment in an unmanned aerial vehicle during forward flight. The unmanned aerial vehicle includes counter-rotating rotor assemblies that are mounted within a duct. Each rotor assembly includes a plurality of rotor blades. The method involves adjusting the rotor blades to have substantially zero pitch. Then rotating the rotor assemblies to produce a virtual plane across the duct. The virtual plane is operative for substantially deflecting air passing over the fuselage away from the duct. In one embodiment of the invention, the method involves the further step of obstructing at least a portion of the bottom of the duct to inhibit air that is flowing across the bottom of the duct from passing into the duct.

12 Claims, 6 Drawing Sheets



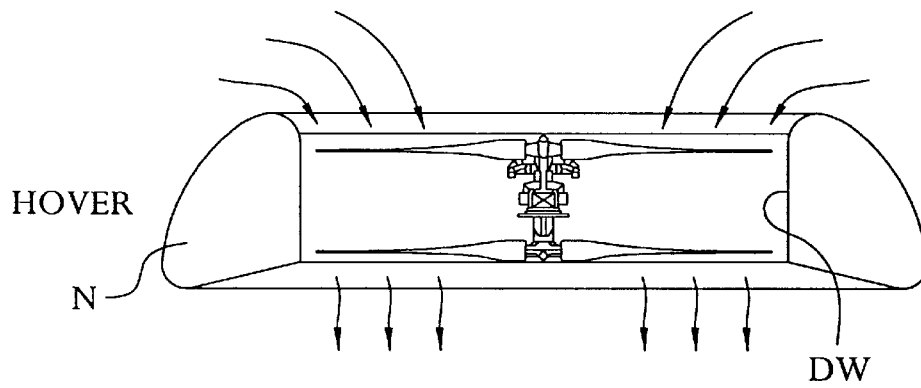


FIG. 1A

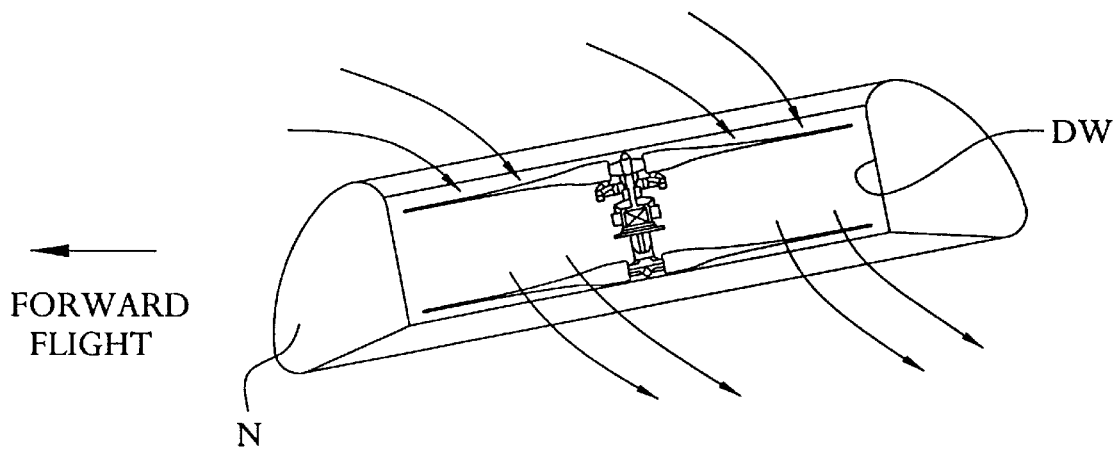


FIG. 1B

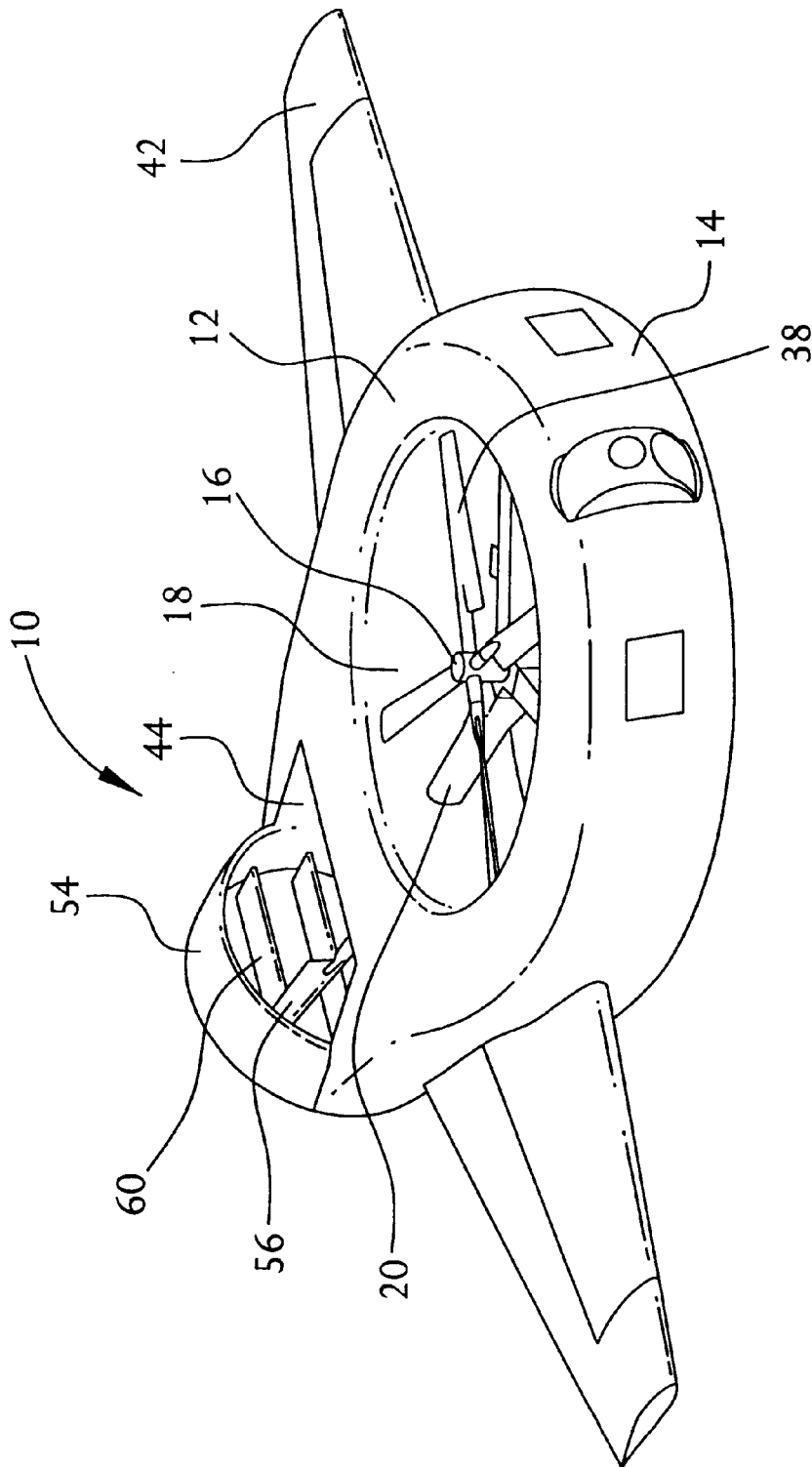


FIG. 2

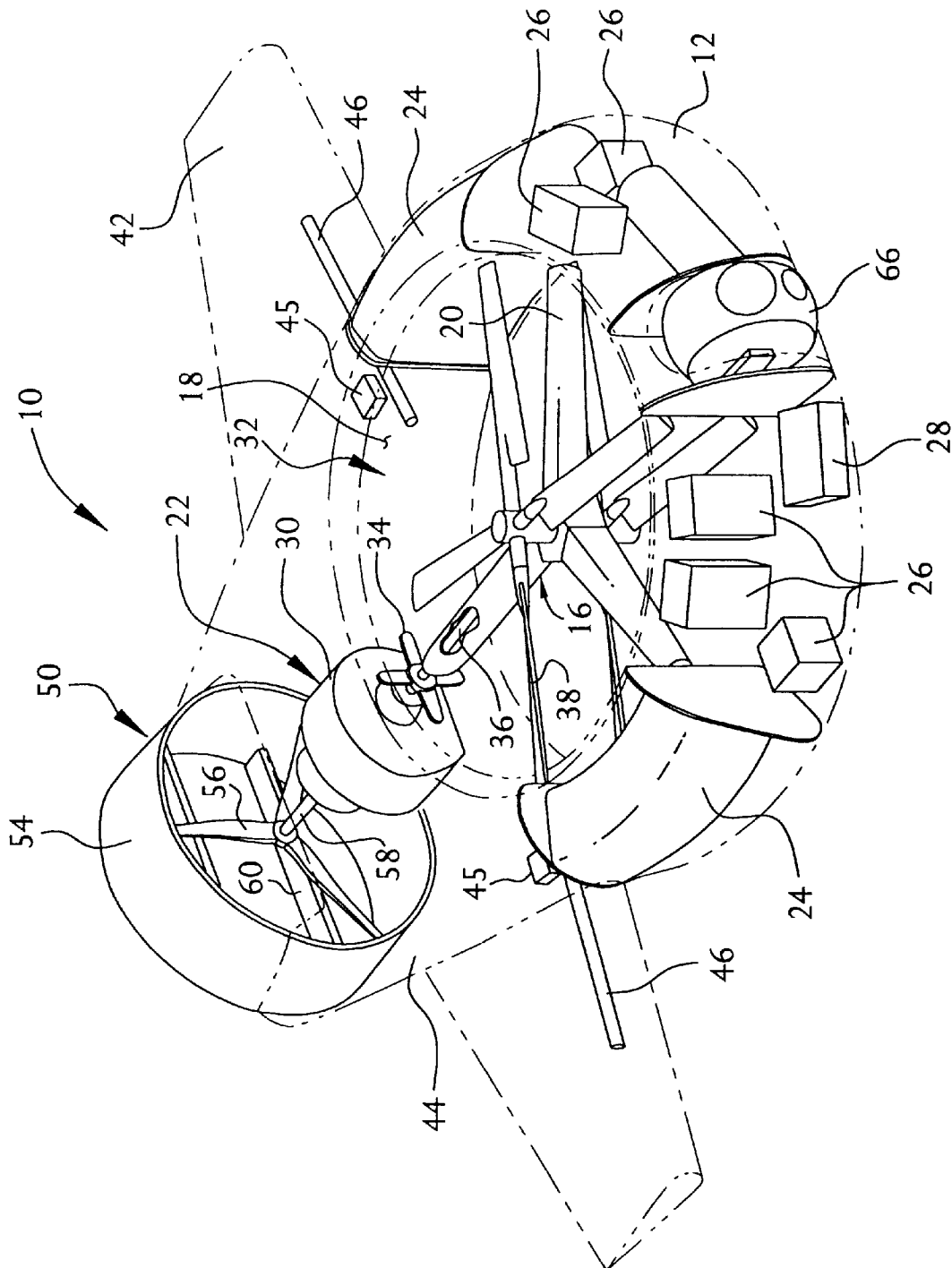


FIG. 3

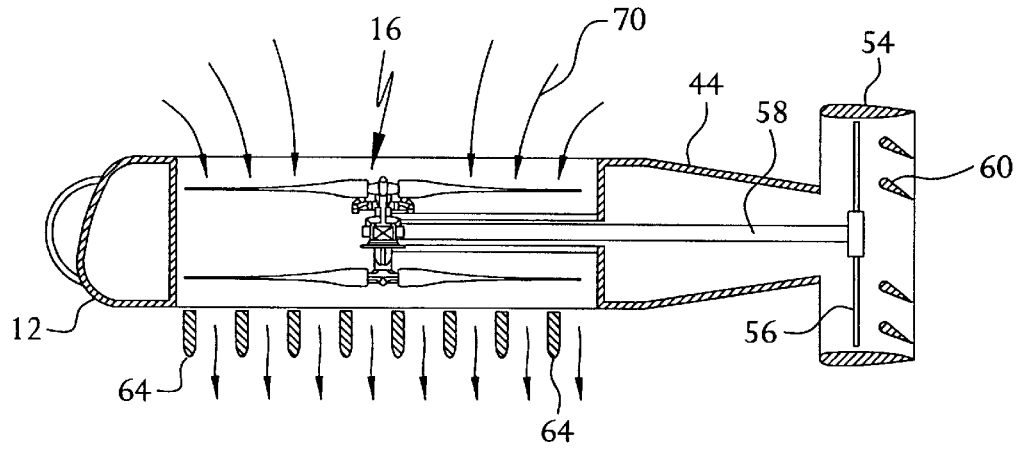


FIG. 4A

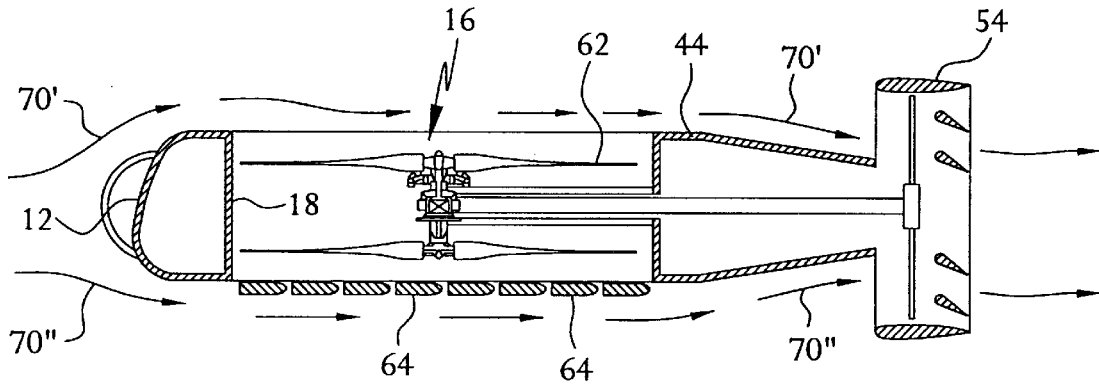


FIG. 4B

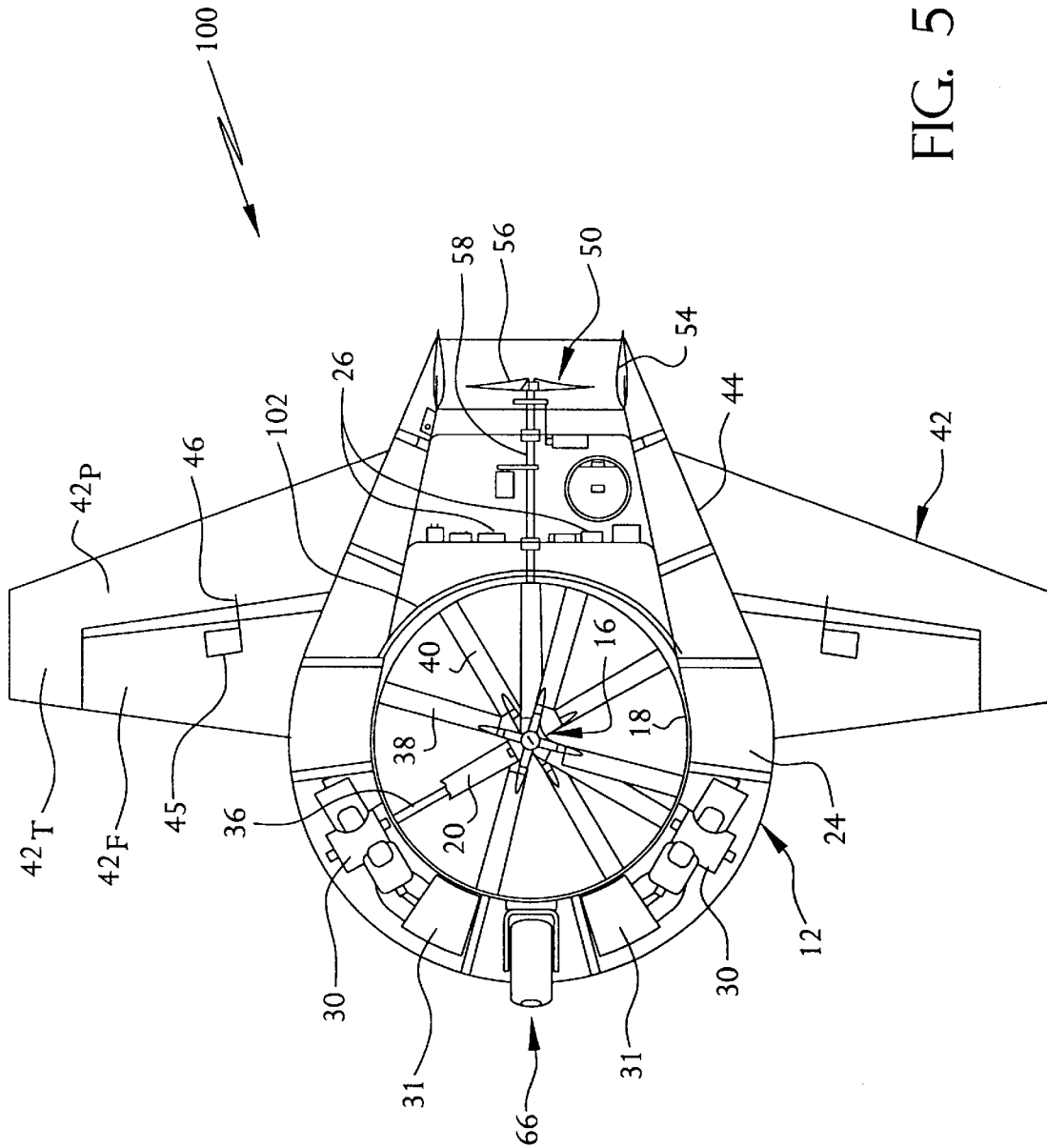


FIG. 5

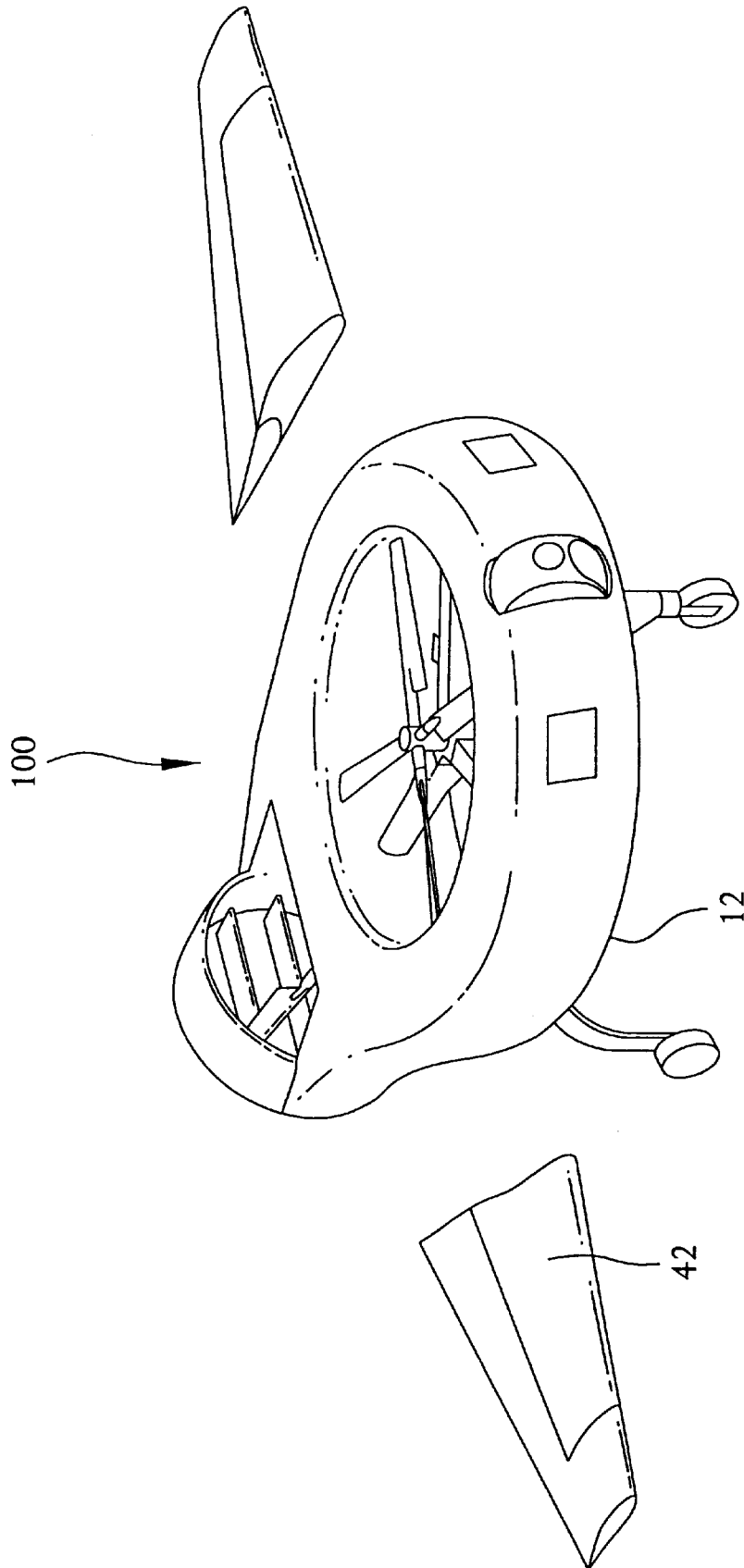


FIG. 6

METHOD OF REDUCING A NOSE-UP PITCHING MOMENT ON A DUCTED UNMANNED AERIAL VEHICLE

RELATED APPLICATION

The instant application is related to commonly-owned, co-pending application entitled, "Unmanned Aerial Vehicle with Counter-Rotating Ducted Rotors And Shrouded Pusher-Prop".

TECHNICAL FIELD

The present invention relates to unmanned aerial vehicles (UAVs). In particular to a high-speed vertical takeoff and landing (VTOL) UAV having a shrouded pair of coaxial, counter-rotating, ducted rotors for providing zero and low speed horizontal and vertical thrust, and a wing and shrouded pusher prop for providing forward translational lift and thrust in high-speed flight.

BACKGROUND OF THE INVENTION

There has been a recent increased emphasis on the use of unmanned aerial vehicles for performing various activities in both civilian and military situations where the use of manned flight vehicles is not appropriate and/or feasible. Such missions include surveillance, reconnaissance, target acquisition and/or designation, data acquisition, communications relay, decoy, jamming, harassment, ordnance delivery, or supply flights. This increased emphasis on the role of UAV's in today's (and tomorrow's) society has led to many advancements in both airframe design and propulsion systems.

There are generally three types of UAV configurations under current development, a fixed-wing type configuration (a fuselage with wings and horizontally mounted engines for translational flight), helicopter type configuration (a fuselage with a rotor mounted above which provides lift and thrust) and ducted type configuration (a fuselage with a ducted rotor system which provides translational flight, as well as vertical take-off and landing capabilities). A wingtype UAV provides several benefits over a helicopter or ducted type UAV. First, and foremost, is the ability of a winged UAV to travel at considerably greater speeds and for longer distances than a conventional helicopter or ducted type UAV. Also, a winged UAV can typically carry a larger mission payload and/or fuel supply than a helicopter or ducted type UAV. As such, fixed-wing UAVs are generally better suited than helicopter or ducted type UAVs for certain mission profiles involving endurance, distance, higher speed and load capability.

Winged UAVs, however, have deficiencies that limit their utility. For example, since winged UAVs require forward motion to maintain lift and therefore are not capable of hovering over a fixed spatial point. As a result, winged UAVs are not very good at delivering ordnance or laser designating targets. Also, winged UAVs cannot take-off and land vertically. Instead, winged UAVs require elaborate launch and retrieval equipment.

Helicopter UAVs can hover over a fixed spatial point and takeoff and land vertically but have limitations when operating in confined areas due to the exposed rotors rotating above the fuselage. Also, helicopter UAVs tend to have a high center-of-gravity (CG) and therefore have limited ability when landing on sloped surfaces or pitching ship decks. A high CG aircraft tends to roll over when landing on steep slopes.

The ability of ducted rotor-type UAVs to take-off and land vertically, combined with their ability to hover for extended

periods of time over a point and operate in confined areas off steep slopes, make a ducted type UAVs ideally suited for real time tactical reconnaissance, target acquisition, surveillance, and ordnance delivery missions for front line tactical units.

Ducted-type UAVs, such as the CYPHER® unmanned aerial vehicle developed by Sikorsky Aircraft Corporation and generally disclosed in U.S. Pat. No. 5,152,478, includes a toroidal fuselage shrouding co-axial, counter-rotating rotors. The rotors are designed to provide the thrust necessary for both vertical and translational flights. As shown in FIG. 1A, aircraft vertical motion of the UAV is provided by maintaining the vehicle fuselage substantially horizontal so that the thrust (downwash) of the rotors provides the necessary lift for the aircraft. When fore-aft or lateral movement of the aircraft is desired, the aircraft fuselage must be "nosed-down" as shown in FIG. 1B in order to generate a horizontal thrust component.

As discussed above, ducted-type UAVs have a relatively slow speed as compared to winged UAVs. One reason for this is that most ducted-type UAV's do not have a separate translational propulsive system. As such, the rotor system must provide both vertical and translational thrust, thus, requiring the full potential of the rotor system to be split.

Another problem associated with a toroidal UAV relates to drag. Referring back to FIG. 1A, if the aircraft were to fly in the forward direction (i. e., to the left in the figure) while oriented horizontally, the airflow passing over the nose N of the aircraft would impact the inner rear wall D_w of the duct. This generates considerable drag on the aircraft. To reduce the drag on the aircraft, it is oriented as shown in FIG. 1B. This orientation of the aircraft causes the airflow to pass through the rotor system, reducing airflow contact with the duct wall D_w .

Another problem associated with conventional ducted-type UAVs is the tendency of the aircraft to experience a nose-up pitching moment. That is, the airflow over the airframe and through the rotor system produces a moment about the aircraft's center of gravity which causes the nose of the aircraft to pitch upward. There have been several attempts made to counter-act this nose-up pitching moment. U.S. Pat. No. 5,152,478 discloses a UAV rotor system wherein cyclic pitch is used to counter-act the nose-up pitching moment during forward translational flight. Although this solution does eliminate the nose-up pitching moment, it also requires a considerable amount of power and does not eliminate the drag on the duct wall.

Another possible option to counter-act the nose-up pitching moment is to optimize the toroidal fuselage airfoil profile. The utilization of an optimized toroidal fuselage airfoil profile to counteract the nose-up pitching tendency of UAVs is disclosed in U.S. Pat. No. 5,150,857. This solution requires that the outer aerodynamic surface of the toroidal fuselage be optimized to provide an asymmetrical toroidal fuselage pressure distribution that produces high lift forces during forward translational flight modes. The high lift forces reduce the required lift provided by the rotor assembly, thereby reducing the undesirable nose-up pitching moment. A reduction in required power is effected by the decreased requirement for rotor lift and the reduced need for superimposed cyclic pitch (moment trim).

While the incorporation of a toroidal fuselage having an optimized outer aerodynamic surface represents a viable option to help counteract the fuselage-induced nose-up pitching moments, this option incurs a manufacturing penalty and may have an adverse effect on higher speed flight characteristics.

A further solution to reducing the nose-up pitching moment in a ducted-type UAV is disclosed in U.S. Pat. No. 5,419,513 wherein ancillary wing structures are incorporated onto the aircraft to counter-act the nose-up pitching moment. More particularly, the ancillary wing structures have an aerodynamic configuration that generates lifting forces to supplement the lifting forces generated by the rotor assembly and the toroidal fuselage.

Although the incorporation of ancillary wings on the aircraft does help counter the nose-up pitching moment caused by translational flight, the aircraft translational thrust is still limited by the amount of horizontal thrust component that can be generated by the rotor system.

A need, therefore, exists for an improved rotor-type UAV which provides increased propulsive capabilities and reduced drag during forward translational flight.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a method for reducing the nose-up pitching moment that occurs during forward flight of a unmanned aerial vehicle.

This and other objects and advantages of the invention are provided by the novel method of controlling airflow over an unmanned aerial vehicle according to the present invention. The unmanned aerial vehicle includes counter-rotating rotor assemblies that are mounted within a duct. Each rotor assembly includes a plurality of rotor blades. The method involves the step of adjusting the rotor blades to have substantially zero pitch. The rotors assemblies are then rotated to produce a virtual plane across the duct. The virtual plane is operative for substantially deflecting the air passing over the fuselage away from the duct.

In one embodiment of the invention, the method involves the further step of obstructing at least a portion of the bottom of the duct to inhibit air that is flowing across the bottom of the duct from passing into the duct.

In a further embodiment of the invention, a negative pressure is generated aft of the duct by increasing the amount of air flowing past the duct on the lower surface of the fuselage. The negative pressure creates a suction force on the air passing over the top of the duct.

As discussed above, ducted rotor aircraft encounter significant nose up pitching moments during forward flight. The present invention counteracts this nose up pitching moment by controlling several aspects of the aircraft. First, the airflow over and under the duct is controlled to minimize the airflow contacting the back wall of the duct. During high speed flight, additional counteracting forces may be needed to prevent the nose-up moments. The present invention addresses this need by creating lifting forces aft of the rotor assemblies, these lifting forces create counter-acting moments that further reduce the nose-up pitching moments. In one embodiment of the invention, the lift forces are created by controlling flaperons on wings mounted to the sides of the aircraft. Additionally, directional lanes located aft of a pusher prop can be controlled to deflect propeller trust downward creating additional lift.

It has also been determined through wind tunnel testing that locating the pusher prop assembly aft of the duct results in reduced drag on the aircraft. More particularly, the pusher prop assembly has been found to draw the turbulent air over the duct that would otherwise flow into the duct and cause drag in high-speed flight. The shroud around the propeller augments this beneficial affect.

Past attempts at high speed ducted rotor aircraft have used rigid retractable covers to conceal the rotor system and

reduce drag. Such covers are relatively heavy and complex. In the present invention, during high-speed flight, the aircraft is in a near level attitude with the rotors operating with nearly a flat pitch. This creates the virtual covers described above which impedes airflow into the duct. By blocking the flow and forcing it to flow over and under the aircraft, drag is reduced without the weight and complexity of rigid covers.

The virtual covers reduce the drag on the aircraft by about one half as much as two rigid covers. As discussed above, in one embodiment of the invention the bottom the bottom of the duct may be obstructed to prevent the entrance of air. The obstructing is provided by one or more deflectors mounted across a portion of the duct to control airflow into the duct from the bottom of the fuselage during forward flight. These deflectors are passive and require no actuation. They are opened and closed automatically based on the airflow through and over the duct. By being passive they save considerable complexity and weight over actively actuated covers. The combination of flat pitch rotors and passive flow deflectors on the bottom of the duct reduces the drag component on the aircraft between the open rotor and completely covered duct by about 80%.

The foregoing and other features and advantages of the present invention will become more apparent in light of the following detailed description of the preferred embodiments thereof, as illustrated in the accompanying figures. As will be realized, the invention is capable of modifications in various respects, all without departing from the invention. Accordingly, the drawings and the description are to be regarded as illustrative in nature, and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

For the purpose of illustrating the invention, the drawings show a form of the invention which is presently preferred. However, it should be understood that this invention is not limited to the precise arrangements and instrumentalities shown in the drawings.

FIG. 1A is a schematic representation of a prior rotor-type unmanned aerial vehicle during hover.

FIG. 1B is a schematic representation of a prior rotor-type unmanned aerial vehicle during forward translational flight.

FIG. 2 is a perspective view of an unmanned aerial vehicle according to the present invention.

FIG. 3 is a perspective view of one embodiment of the unmanned aerial vehicle in FIG. 2 illustrating many of the internal components.

FIG. 4A is a schematic representation of the unmanned aerial vehicle according to the present invention during hover.

FIG. 4B is a schematic representation of the unmanned aerial vehicle according to the present invention during forward translational flight.

FIG. 5 is a schematic representation of a preferred embodiment of the unmanned aerial vehicle according to the present invention.

FIG. 6 is a perspective view of one embodiment of the unmanned aerial vehicle which illustrates the wings detached from the fuselage.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings wherein like reference characters identify corresponding or similar elements

throughout the several views, FIG. 2 illustrates a perspective view of one embodiment of an unmanned aerial vehicle (UAV) 10 according to the present invention. The UAV 10 includes a fuselage 12 with a toroidal portion 14 having a generally hemicylindrical aerodynamic profile.

A rotor assembly 16 is mounted within a duct 18 that extends substantially vertically through the fuselage 12. A plurality of struts 20 extend between the fuselage and the rotor assembly 16. In the preferred embodiment illustrated in the figures, there are three struts 20 mounted in the fuselage 12. The support struts 20 are rigidly attached to the rotor assembly 16 and the fuselage 12, and are operative for supporting the rotor assembly 16 in a fixed co-axial relation with respect to the duct 18. The support struts 20 also provide structural rigidity to the aircraft duct 18 to prevent flight and ground loads from distorting the fuselage 12.

In order to minimize weight, the support struts 20 are preferably formed as hollow structures that can be used as conduits for interconnecting operating elements of the UAV 10. For example, the engine drive shaft (identified by the numeral 36 in FIG. 3) is routed through one of the support struts 20. In addition, the electrical wiring for various operating components in the aircraft 10 may be routed through the other support struts 20.

The fuselage 12 and the plurality of support struts 20 can be made from various types of high tensile strength materials, such as composite and metal. The fuselage 12 includes a plurality of accessible internal bays (shown in FIG. 3) for housing and/or storing aircraft flight and mission components. For example, referring to FIG. 3 which illustrates one embodiment of the UAV 10 according to the present invention, the compartments may be used to house a powerplant subsystem 22, including fuel tanks 24, flight control equipment 26 including data transmitters and receivers, a power conditioning unit 28, and sensors 66, such as a forward looking infrared radar (FLIR) sensor. In an alternate UAV configuration (shown in FIG. 5), engines are mounted within the bays and the avionics equipment is mounted in the aft fuselage. The various components are preferably positioned within the compartments to balance the aircraft about the center of the rotor assembly.

The structural configuration of the UAV 10 in one embodiment is described in more detail in U.S. Pats. Nos. 5,152,478, 5,277,380, and 5,419,513, which are incorporated herein by reference in their entirety.

The powerplant subsystem 22 includes one or more fuel tanks 24, an engine 30, a drive train assembly 32, and a cooling fan 34. The fuel tanks 24 are disposed within appropriate internal bays, preferably in opposed equipment bays to maintain a relatively constant center of gravity for the UAV 10 during flight operations.

A drive train assembly 32 is operative for transferring power developed by the engine 30 to the rotor assembly 16 by means of a drive shaft 36. The drive train assembly 32 may be of the type disclosed in commonly-owned, U.S. Pat. No. 5,226,350, which is incorporated herein by reference in its entirety.

In an alternate, and more preferred embodiment of the UAV 100 shown in FIG. 5, there are two engines mounted within the internal bays. Each engine 30 is preferably mounted forward of a fuel tank 24. Mufflers 31 can be mounted adjacent to each engine 30 to reduce engine noise levels. The engines 30 are each engaged with the rotor system 16 by means of a drive shaft 36 that extends through a support strut 20. The shafts 36 are preferably constructed of thin-wall aluminum tube for high strength and low

weight. Flex couplings (not shown) are used to attach the shaft 36 to the engine 30 and the rotor assembly 16 to permit angular misalignment while transmitting torque.

The two engine embodiment shown in FIG. 5 allows the aircraft to continue to operate in the event of an engine failure. An overrunning clutch is incorporated into the system to automatically disengage an inoperative engine from the system. The engines 30 are preferably mounted to the airframe with four shock mounts. In light of the location of the engine mounts in the front of the airframe, the mounts can also be used to support the landing gear.

A cross-feed line 102 is preferably attached to each fuel tank to allow fuel to migrate between the tanks 24. This permits that aircraft to maintain balance under normal flight conditions. It also allows both engines to be fed in the case of one tank 24 running dry.

In the embodiment of the invention shown in FIG. 5, a separate cooling fan is not needed to cool the engines since air can be channeled into the compartment via an inlet on the airframe 12.

The rotor assembly 16 includes a pair of multi-bladed, counter-rotating rotors 38,40, coaxially aligned with the centerline of the duct 18, and a coaxial transmission subassembly (not shown). The coaxial transmission subassembly may be of the type disclosed in commonly-owned, co-pending U.S. Pat. No. 5,226,350. The rotors 38, 40 are aerodynamically "shrouded" by the fuselage 12.

The counter-rotating rotors 38, 40 are preferably of the rigid rotor type (as opposed to articulated rotors) to reduce the complexity and weight of the rotor assembly 16. Each counter-rotating rotor 38, 40 preferably includes a plurality of blade assemblies, which may be of the type disclosed in commonly-owned, co-pending U.S. Pat. No. 5,364,230, which is incorporated herein by reference in its entirety. In this type of rotor design, blade pitch changes induced in the counter-rotating rotors 38, 40, i.e., cyclic and/or collective pitch inputs, can be utilized to generate lift, pitch, roll, and yaw control of the UAV 10. In the embodiment of the UAV 100 shown in FIG. 5, there are four blade assemblies on each counter-rotating rotor 38,40.

In one preferred embodiment of the invention, the blades on the blade assemblies are rigid hingeless metal blades. The hingeless metal design is aerodynamically efficient, less costly than a composite blade, allows for additional control authority, and is less susceptible to foreign object damage. The blades preferably have a constant chord, are linearly twisted by about 25 degrees, and utilize a low Reynolds number airfoil. Alternatively, the blade can be made from wood with a metal leading edge and wrapped with a thin layer of fiberglass. The blades can also be tapered in chord and airfoil thickness from root to tip depending upon mission application. The blade tip speed of the rotor system is preferably about 62500 fps. This blade tip speed results in a rotor system that has low noise and reduced structural weight.

As will be discussed in more detail below, the pitch of the rotors can be adjusted to control the airflow over the shroud 12 and into the rotor assembly 16. Such control of the airflow can create a lifting component on the shroud 12 that augments the lift provided by the counter-rotating rotors 38, 40.

In one embodiment of the UAV 10, wings 42 are attached to and extend laterally outward from the sides of the aircraft fuselage 12. More particularly, the fuselage 12, in addition to its toroidal portion 14 that surrounds a portion of the duct 18, includes an aft fuselage portion 44 or empennage (also

referred to herein as a fairing). The aft fuselage **44** tapers as it extends rearwardly from the toroidal portion **14** of the shroud **12**. The wings **42** are preferably attached to the aft fuselage **44** at approximately its midplane.

The aerodynamic configuration of the wings **42** of the UAV **10** is selected to provide high lifting forces and a large nose-down pitching moment in forward translational flight. In addition, the wings **42** have a low aspect ratio so that the UAV **10** is maintained at a reasonable size. The wings **42** preferably taper outward from the fuselage **12**. Each wing **42** preferably has a symmetric or low camber airfoil section. Those skilled in the art would readily appreciate the diverse wing arrangements that can be incorporated into a UAV according to the present invention. Wing arrangements are dictated by the desired aircraft performance.

Preferably, at least a portion of the wings **42** is pivotally mounted so that the angle of attack of the wings **42** can be varied depending on the aircraft's mission. For example, in one embodiment of the invention shown in FIG. 3, the entire wing **42** could be pivotally mounted to the airframe. The wings **42** would then be angled so as to provide additional lift when the aircraft is in a loiter mode of operation. Conversely, the wings **42** would be highly angled if the mission requires a high degree of maneuverability. To control pivoting of the wings **42**, an actuator **45** is mounted within the fuselage **12** near each wing **42**. The actuator **45** is engaged with a drive rod **46** that is attached to the wing **42**. The actuator **45** is preferably an electrical servo that is controlled by signals from an onboard computer that regulates the amount that the actuator rotates the drive rod **46** about its longitudinal axis. The rotation of the drive rod **46** changes the angle of attack of the wing **42**. As is shown in the illustrated embodiment, there are two actuators **45**, one for controlling each wing **42**. This allows the wings **42** to be independently pivoted. It is also contemplated that a single actuator can be used to pivot both wings if independent pivoting is not desired.

In a more preferred embodiment of the invention shown in FIG. 5, only a portion of the wing **42** is pivotable. In this embodiment, each wing **42** includes a fixed stub portion **42_F** and a pivotal portion **42_P**. The pivotal portion **42_P** preferably includes a flapener hingedly mounted to the trailing edge of the wing **42**. An actuator **45** mounted within the fixed portion **42_F** controls the pivoting of the pivotal portion **42_P**. The flapener **42_P** preferably has a deflection range from about 45 degrees trailing edge down to about 15 degrees trailing edge up. As shown in FIG. 5, it is preferable that the pivotal portion **42_P** also includes a pivotal tip end or cap **42_T** which functions as an aerodynamic and mass balance to facilitate flap actuation. The pivoting tip end reduces control loads on the actuator **45** by approximately 55%, thereby increasing actuator life and reliability. Those skilled in the art would readily appreciate the diverse pivotal wing arrangements that can be incorporated into a UAV according to the present invention.

Referring to FIG. 6, the wings **42** are preferably removably attached to the fuselage **12**. This permits operational personnel to detach the wings **42** from the fuselage **12** during storage or transit. The wings **42** are then reattached to the fuselage **12** prior to use. The wings are mounted using conventional bolts or quick disconnect couplings. Since the actuator **45** is mounted within the fixed portion **42_F** of the wing in the embodiment of the invention shown in FIG. 5, only electrical control lines need to connect from the UAV fuselage **12** to the wing **42**.

It is contemplated that wings with different geometries and aerodynamic characteristics can be attached to the

airframe **12** depending on the specific aircraft mission. Also the fuselage **44** has a straight or flat interface surface on the left and right sides which forms a mating surface for the wing. This smooth flat surface simplifies wing attachment and removal.

In order to provide translational thrust, the UAV **10** includes a pusher prop **50** mounted to the rear of the aircraft **10**. More particularly, the pusher prop (or propeller) **50** is mounted to the rear of the aircraft with its rotational axis oriented substantially horizontal. The pusher prop **50** includes a plurality of blades **56**, which in the illustrated embodiment there are two blades **56** with a diameter of about 20 inches. The propeller **50** is mounted to a drive shaft **58** which, in turn, is engaged with a power unit. In the preferred embodiments, the power unit which drives the propeller **50** is the engine **30** that is used to power the rotor assembly **16**. As shown in FIG. 5, the propeller drive shaft **58** is engaged with the engines **30** through the rotor systems gearbox. A flexible coupling is incorporated between the gearbox and the drive shaft **58** to allow for shaft misalignments. The pusher prop **50** is designed to provide the aircraft's forward thrust in high-speed flight.

The propeller **50** operates at about 7000 RPM and preferably is of a hingeless rigid design. The blades **56** are mounted so that the collective pitch of the blades can be controlled. In order to improve aircraft agility in low speed flight, the propeller is designed with reverse pitch capability. The propeller **50** in the preferred embodiment is designed with a tip speed of about 637 fps but it could be operated at any other suitable propeller tip speed.

A prop shroud **54** is formed on the aft fuselage **44** around the pusher prop **50** and preferably has a cylindrical or frustoconical shape. The cross-sectional shape of the shroud **54** is preferably configured as an airfoil to provide the shroud **54** with some lift. The lift on the shroud **54** creates a moment about the aircraft's center of gravity that stabilizes the aircraft in the pitch and yaw directions. The shroud **54** also protects the propellers from environmental contact, increases the propeller efficiency and reduces the aircraft's acoustic signature.

Mounted on the shroud **54** aft of the pusher prop **50** are one or more directional vanes **60**. The vanes **60** are configured to direct the exhaust from the pusher prop **50** in a particular direction. Preferably, the vanes **60** are pivotally mounted to the shroud **54** to permit the exhausted air to be channeled in a controllable manner. For example, during transition it is desirable to angle the vanes **60** so as to channel the air downwardly, thereby augmenting the vertical lift provided by the rotor assembly **16**. In high-speed flight, the vanes **60** function as elevators on the aircraft to provide pitch control for the vehicle.

Referring to FIGS. 2, 4A and 4B, the aft fuselage **44** preferably has a contour which assists in channeling the air into the pusher prop **50**. In the illustrated embodiment, the top surface of the aft fuselage **44** angles downwardly toward the shroud **54**. Similarly, the lower surface of the aft fuselage **44** angles upward toward the shroud **54**. This results in a channeling of the airflow into the pusher prop **50**.

As discussed above with respect to FIG. 1B, during forward flight of a conventional toroidal fuselage ducted-type UAV, the airflow into the duct impacts the wall of the duct D_w causing considerable drag on the aircraft and increases the nose up pitching moment experienced by the fuselage. For the near level body high speed flight orientation of this invention, air also enters from the bottom of the duct and impacts the wall of the duct D_w and causes the

same large drag increase. In one embodiment of the present invention, the UAV 10 reduces the drag caused during forward flight by controlling the flow of air into the duct 18.

Referring to FIG. 4A, the UAV 10 is shown in its vertical takeoff and hover mode with the airflow 70 funneling downward through the rotor assembly 16 as is conventional in the prior UAV designs. FIG. 4B illustrates the UAV 10 according to the present invention in high-speed flight. As shown, the airflow 70' that passes over top of the nose of the aircraft tends to angle downward into the rotor assembly 16. To prevent the air from entering the duct 18, the rotors 38, 40 are adjusted so as to have approximately zero pitch, i.e., substantially flat pitch. At near zero pitch, the rotational speed of the rotors 38, 40 create a virtual plane 62 across the top and bottom of the duct 18. This virtual plane 62, which is coplanar with the rotors 38,40, deflects the air passing over and under the vehicle away from the duct 18. As a result, the passing air does not impact the rear wall of the duct D_w . Instead, the air is channeled into the pusher prop 50. The pitch of the rotors 38,40 is changed slightly both collectively and cyclically as the air vehicle's flight speed changes to minimize drag. The benefits of the virtual plane 62 are primarily present at flight speeds where the aircraft is supported entirely by the wings 42 and fuselage 12.

To further reduce aircraft drag the present invention incorporates one or more deflectors 64 on the lower surface of the aircraft. The deflectors prevent airflow from entering the duct 18 from the lower surface of the UAV 10. Referring to FIGS. 4A and 4B, the UAV 10 is shown with deflectors 64 mounted to the lower surface of the fuselage 12 below the rotor assembly 16. The deflectors 64 are attached to the aircraft via hinges and are free to pivot.

When in the hover mode, the downwash from the rotors causes the deflectors 64 to open as shown in FIG. 4A. In forward flight, the natural high pressure on the bottom of the aircraft causes the deflectors 64 to close off the duct, thereby preventing airflow 70" from entering into the duct from the lower surface. As such, the airflow 70" across the bottom of the UAV 10 passes the duct 18 and is channeled into the pusher prop 50 as shown in FIG. 4B.

A 40% scale model of a UAV 10 incorporating many of the aspects of the invention described above was tested to assess the effect that rotor speed has on drag. The test results proved that by increasing the speed of the rotors 38, 40, the overall drag on the UAV 10 could be reduced. The UAV was also tested with the deflectors 64. The incorporation of the deflectors 64 reduced drag on the aircraft by almost 80% over an unpowered open rotor configuration.

The low speed flight control and flying qualities of a UAV according to the present invention are similar to those described in U.S. Pat. No. 5,152,478. The high speed control and flying qualities of the UAV 10, on the other hand, are similar to conventional fixed wing aircraft. In high speed flight, the pivotable flap portions on the wings act as ailerons for providing roll control.

Directional vanes in the shroud function as elevators. While a vertical vane is not shown within the shroud in the figures, it could readily be added to provide yaw control if mission requirements dictate its need.

In order to transition the UAV 10 from hover flight mode to forward flight mode, the rotor assemblies, flaperons and pusher prop must be controlled to blend low speed rotor control into high-speed wing and elevator control. The following is a discussion of one very efficient transition profile. The aircraft is capable of flying in transition mode anywhere from zero to 20 degrees of body attitude. To begin

transition to fixed wing mode the UAV 10 is pitched about five degrees nose down. At about 5 kts the aircraft begins to rotate nose up. The aircraft reaches 10 degrees angle of attack upon reaching 20 kts. The aircraft remains at 10 degrees angle of attack out to 55 kts. As the aircraft accelerates from 20 kts to 55 kts, rotor thrust is gradually reduced as wing lift increases. This is described in U.S. Pat. No. 5,152,478 and U.S. Pat. No. 5,150,857, which are both incorporated herein in their entirety.

The UAV according to the present invention is capable of zero degree flaperon wing borne flight at 55 kts and will begin to nose down as speed is further increased. Above 55 kts the UAV flies like a typical fixed wing aircraft. Transition back to helicopter mode is accomplished by reversing the steps described above.

Although the invention has been described and illustrated with respect to the exemplary embodiments thereof, it should be understood by those skilled in the art that the foregoing and various other changes, omissions and additions may be made therein and thereto, without parting from the spirit and scope of the present invention.

What is claimed is:

1. A method for reducing a nose-up pitching moment in an unmanned aerial vehicle during forward flight, the unmanned aerial vehicle including counter-rotating rotor assemblies mounted within a duct, the duct extending downwardly through a fuselage in the unmanned aerial vehicle, each rotor assembly including a plurality of rotor blades, the method comprising the steps of:

adjusting the rotor blades to have substantially zero pitch; rotating the rotor assemblies to produce a virtual plane across the duct, the virtual plane operative for substantially deflecting air passing over the fuselage away from the duct.

2. The method of claim 1 further comprising the step of providing a plurality of passively pivotable deflectors on the bottom of the fuselage, the deflectors extending across the duct, the air flow across the bottom of the fuselage causing the deflectors to pivot and substantially close off the bottom of the duct.

3. The method of claim 1 further comprising the step of obstructing at least a portion of the bottom of the duct to inhibit air that is flowing across the bottom of the duct from passing into the duct.

4. The method of claim 1 wherein the unmanned aerial vehicle includes a pusher propeller, the method further comprising the step of generating a negative pressure aft of the duct by increasing the amount of air flowing past the duct by rotating the pusher prop, the negative pressure creating a suction force on the air passing over the top of the duct thereby drawing the air past the upper surface of the duct.

5. The method of claim 1 further comprising the step of increasing the speed of the rotors.

6. The method of claim 1 wherein the unmanned aerial vehicle includes a fuselage extending aftward from the duct and a pusher prop assembly mounted aft of the fuselage, the pusher prop assembly further including a shroud disposed about a pusher prop and vertically spaced apart directional vanes attached to the shroud aft of the pusher prop, the method further comprising the step of controlling the orientation of the directional vanes for controlling the direction of air flow out of the pusher prop assembly to create a lift component on the vehicle aft of the duct for counteracting nose-up pitching moment.

7. The method of claim 1 wherein the unmanned aerial vehicle includes a pair of wings attached to the fuselage, the wings having a pivotable trailing edge and tip portion, the

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method further comprising the step of pivoting the trailing edge and tip portion to create a lift component on the vehicle aft of the duct.

8. The method of claim 1 further comprising the step of at least partially closing off the bottom of the duct to increase the amount of air flowing past the lower surface of the duct and aft of the aircraft, the increased air flow generating a suction on the upper surface for drawing air past the top of the duct.

9. The method of claim 1 further comprising the step controlling the air flowing past the upper and lower openings of the duct by generating a higher air flow past the lower opening of the duct and aft of the aircraft, the higher air flow on the lower surface of the aircraft generating a negative pressure on the upper surface of the aircraft aft of the duct opening, the negative pressure suctioning the air across the upper opening of the duct and thereby reducing the nose up pitching moment on the aircraft.

10. A method for restricting air flow into a duct of an unmanned aerial vehicle during forward flight, the unmanned aerial vehicle including counter-rotating rotor assemblies mounted within the duct, the duct extending downwardly through a fuselage in the unmanned aerial vehicle, each rotor assembly including a plurality of rotor blades, the method comprising the steps of:

- adjusting the rotor blades to have substantially zero pitch;
- rotating the rotor assemblies to produce a virtual plane across the duct, the virtual plane operative for substan-

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tially deflecting air passing over the fuselage away from the duct; and

providing a plurality of pivotable deflectors on the bottom of the fuselage, the deflectors extending across the duct, the air flow across the bottom of the fuselage causing the deflectors to pivot and close off at least a portion of the bottom of the duct, thereby increasing the amount of air that passes under the fuselage, the increased air flow across the bottom of the fuselage generating a negative pressure aft of the duct on the top of the fuselage that creates a suction on the air passing over the duct.

11. The method of claim 10 wherein the unmanned aerial vehicle includes a pusher prop assembly mounted aft of the duct, the pusher prop assembly further comprising a shroud disposed about a pusher prop and vertically spaced apart directional vanes attached to the shroud aft of the pusher prop, the method further comprising the step of controlling the orientation of the directional vanes for controlling the direction of air flow out of the pusher prop assembly to create a lift component on the vehicle aft of the duct for counteracting nose-up pitching moment.

12. The method of claim 10 further comprising the step of increasing the speed of the rotors.

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