Lift Fans as Gyrosopes for Controlling Compact VTOL Air Vehicles: Overview and Development Status of Oblique Active Tilting

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Able to provide dual-fan VTOL air vehicles with exceptional pitch agility and stability, lift-fan oblique active tilting (OAT) is outlined and modeled using support data from our two flying prototypes. Comparisons to OAT - which generates large and immediate gyroscopic controlling moments - show conventional thrust vectoring to be an order of magnitude less effective. Experimental observations of OAT also improving yaw and roll while enabling pitch control are here expounded as well, and its potential for providing independent, 6-axis vehicle control is investigated with promising results.

Notation

\[ I_{x, y, z} \] aircraft mass moment of inertia about pitch axis
\[ I_{r, p, q} \] propeller pod inertia about roll and yaw axes, respect.
\[ l_{p} \] propeller pod inertia about tilt axis
\[ l_{s} \] propeller inertia about spin axis
\[ k_{p, r} \] proportional and derivative feedback gains
\[ \Omega \] propeller net torque
\[ T, \delta_{s} \] propeller nominal and differential thrusts
\[ h, s \] vert & hor dist of pod tilt axis from a/c mass center
\[ \alpha, \beta, \gamma \] propeller longitudinal, lateral and true tilt angles
\[ k_{mp, mr} \] pitch- and roll-mode constants
\[ \phi \] vane deflection angle, from a/c vertical
\[ \lambda \] tilt path direction relative to longitudinal
\[ \theta, \psi \] aircraft pitch, roll and yaw angles
\[ \omega \] propeller rotational speed (radians/unit time)

Introduction

The breakthroughs required in personal air mobility to enable on-demand, point-to-point transportation systems [1] in large part concern an air vehicle’s ability to access and operate in confined environments. Satisfying this condition necessitates VTOL air vehicles being more compact for a given payload, but maintaining effective vehicle control becomes increasingly difficult as their size reduces [2]. By definition the available moment arms decrease in length, and proper control of the vehicle entails larger and larger forces – forces which, at some point, conventional control devices can no longer provide.

One type of control device which does not rely on moment arms is the simple gyroscope. It, or rather pairs of them, directly generate the large moments required to change the attitudes of satellites and space stations within short time frames[3, 4]. Unfortunately, though they have been used or proposed as such for research [5], [6], weight limitations make them impractical for general use in air vehicles.

This paper describes the method’s application to pitch control of dual-fan VTOL air vehicles and its ongoing development at Gress Aerospace. Illustrated schematically in Figure 1, lift-fan oblique active tilting (OAT) is used in subscale prototypes with excellent results and, consequently, full scale is planned (Figure 2).

Fig. 1. Schematic of lift-fan oblique active tilting (OAT) for VTOL air vehicle pitch control – from resulting thrust-, torque- and gyroscopic moments.

However, the present author found that, by utilizing the vehicle’s lift-fans themselves as control moment gyroscopes (CMGs), one had the basis for a powerful control system which possessed minimal weight and did not depend on vehicle geometry or scale. As well, with fans imparting aerodynamic-torque moments along with gyroscopic ones, it appeared to have more to offer than a control system consisting of just conventional CMGs.

As well, OAT can provide more than just stability and control in the conventional sense: independent control of all six axes is possible using the dual-axis version.

Background

First proposed and demonstrated [7] by the author using a small electric model in 2003, OAT – or Opposed Lateral Tilting (OLT) as it was then called – recently has met with several key advances which – being either concept-specific or industry-wide – provided a second micro-sized electric model, the 13-ounce MicroVader (Figures 4, 5), with exceptional flight characteristics (Figure 2). These advances were:

- Alignment of OLT theory with actual practice of using oblique tilting; 2003 rate-gyro was incorrect.
- Introduction of gearless outrunner electric motors.
- Advent of lithium polymer batteries.
- Location, incidence and camber of horizontal stabilizer negate aircraft pitch-up at forward speeds.

The attendant success of the MicroVader – with its single-axis tilting providing sound helicopter-like control – allowed work to commence on a larger and more flexible application of OAT: This is the recently completed, dual-axis, 14-lb. eVader (Figures 5, 6), just having recently completed hover testing (Figure 2).

Fig. 2. Top: Our flying prototypes. Bottom: Concept Personal Air Vehicle (PAV). All are OAT controlled.

Fig. 3. Left: The three pitch control moments generated by tilting propellers in oblique (non-longitudinal) direction: gyroscopic (G), torque (T) and thrust vector (H). R is pitch component of inertial reaction to single-axis tilting, effectively mitigated by \( C_{p} \). Right: Combined OAT moment compared to modeled control vanes’ below propellers with same moment arm and tilt control function. Vehicle pitch rate is proportional to area under respective curve, showing OAT many times more effective.

* and eliminated with dual-axis tilting.

Fig. 4. Top: 13-oz., single-axis OAT Micro-Vader. Bottom left: Propeller pod close-up. Bottom right: Propeller tilts along fixed, non-longitudinal path.

Fig. 5. Relative sizes of MicroVader (left) and eVader.

Fig. 6. Top: 14-lb., dual-axis OAT eVader. Bottom left: Longitudinal tilting mechanism located at fuselage. Bottom right: Independent lateral tilting mechanism is contained within propeller pod.
During this period independent research in France by R. Lozano et al [8] determined that oblique tilting appeared to be effective and practical, and that their experimental results were very promising.

**Current Efforts**

With its limited electronics connected to exactly emulate the MicroVader’s single-axis OAT (dOAT), the eVader presently hovers and maneuvers as well as the smaller vehicle. However, as will be shown, there is much to be gained by taking full advantage of its dual-axis OAT (dOAT) capability: the provision of even better control response and the potential for independent, 6-axis control. It will allow, for example,

- vertical takeoffs and landings from severely sloped terrain (approx. 30°). See Figure 7.
- remaining perfectly level in hover while, say, front-loading materiel and personnel.
- remaining stationary – or in position – while pitching and yawing to track a target (Figure 7).
- extreme maneuvering in three dimensional space all the while pointed at a specific target.

![Figure 7](image1.png)

**Fig. 7.** eVader depicted in (a) normal hover mode, and (b) stationary pitching mode for tracking targets - and takeoff and landing from sloped terrain. Fan torques maintain equilibrium in this mode.

With basic hover testing of the eVader completed, work has begun reconfiguring its electronics from dOAT emulation to dOAT. This will be performed in stages, with extensive testing done at each. Some aspects of dOAT can be exploited without programmable electronics, and these are being considered first.

Concurrent with this effort, the eVader is being readied for forward speed and maneuverability trials.

For it’s possible role as a UAV, various power storage and energy sources are being looked at to increase the eVader’s range and endurance beyond that available from its current lithium polymer batteries. With electric prop-motors being the drive system of choice for OAT – due to the necessary articulation of the propeller nacelles or pods for control – the challenge is to find a source where the energy density of the complete lift/propulsion system is comparable to that of a conventional one. One possibility is a central turboshift driving an electric generator which in turn powers the two prop-motors. Indications are that a vehicle so equipped will be no heavier than one with an IC engine and drivetrain (to the prop-fans) - mainly because of the latter’s required heavier supporting structure.

**Planned Future Work**

Appendix A of this paper outlines the key features of a compact VTOL personal air vehicle (PAV) enabled by OAT (Figure 8), and discusses the benefits it would offer in relation to other vehicle types. With these being numerous, the intent for some time at Gress has been to construct a full size PAV, and all of its efforts – the development of the MicroVader and eVader sub-scale prototypes – to date have been directed towards that end.

The next step envisioned is in fact the building and testing of a full size prototype, but one which is essentially a scaled-up (2.5x) eVader, that is, powered by batteries of 10-minute duration and lacking a fuselage proper. The idea is to introduce as few new elements as possible to expediently and inexpensively prove OAT’s viability at the larger scale. Then, when this is completed, the prototype will be upgraded with the proper energy source, fuselage, and the remaining elements comprising a PAV.

In this Paper

This paper is divided into two main sections. The first is an overview and explanation of the OAT control concept, and the second a theoretical analysis of OAT vehicle control response and stability with comparisons to other systems, as well as some of the more advanced features associated with dual-axis tilting, dOAT.

![Figure 8](image2.png)

**Fig. 8.** Relative sizes of MicroVader, eVader and full-size electric PAV incorporating OAT.

**Overview of Oblique Active Tilting**

Gyroscope Pitch Moments from Fan Lateral Tilting

Representing the lift fans with simple spinning discs, Figure 9 shows how a vehicle’s attitude is changed by tilting them simultaneously towards - or away from - one another. Peculiar to gyroscopes, an unbalanced moment \( M_y \) is generated during their tilting whose direction is at right angles to their tilt axes. This is the moment used to initiate control and dynamically stabilize the pitch attitude of our compact VTOL air vehicle.

![Figure 9](image3.png)

**Fig. 9.** Principle of controlling vehicle attitude using fan gyroscopic moments: (a) oppositely spinning disks in neutral orientation; (b) disks being tilted equally towards one another by unseen actuators, generating gyroscopic moment \( M_y \); (c) resulting rotation of vehicle about axis \( y-y \).

Another way of understanding this process is to consider it in terms of conservation of angular momentum. In Figure 9 the discs are spinning oppositely but not tilted, and the vehicle is assumed to be initially at rest (not rotating about its pitch axis \( y-y \)), so the net angular momentum of the system is zero. Once the discs are tilted away from the vertical (Figure 9b), however, there will be a component of their angular momentum about axis \( y-y \). Therefore, for angular momentum to be conserved – that is, for it to remain zero for the entire system - the vehicle containing the spinning discs must begin rotating in the opposite direction (Figure 9c).

In the case of space vehicles using this method for attitude control, returning the spinning discs to their neutral orientation will halt rotation of the vehicle, where it will rest at the new attitude. In the case of air vehicles, however, there will normally be aerodynamic forces at work tending to halt or limit rotation of the vehicle without having to return the fans to neutral.

**International Space Station:**

Thrusters Desaturate Control Moment Gyroscopes

The gyroscopic portion of OAT control is identical to the main attitude control system of the International Space Station (ISS), shown in Figure 10a: the simultaneous, opposed tilting of pairs of control moment gyroscopes (Figure 10b) to effect an attitude change about a particular axis. This is the American part of the ISS’s control system. Note that, since gyroscopic moments are generated only while the spinning CMGs or fans (in our case) are being tilted and that these moments are proportional to the tilt rate, if the CMGs reach their physical limits they can no longer effect control of the vehicle. In this case the system is said to be saturated, and is where the Russian part of the control system begins operation. Occasionally their maneuvering thrusters must be fired to correct the ISS’s attitude and to de-saturate the CMGs (ie, allow them to be returned to their neutral orientations).

![Figure 10](image4.png)

**Fig. 10 (a) ISS in orbit; (b) one of four onboard CMGs which control it’s attitude about the three axes.**

As was mentioned in the introduction, proposals for using onboard CMGs for stabilizing and controlling air vehicles have been made before, but none considered using the lift fans themselves as CMGs. There are, however, several advantages to doing so, the most obvious being a substantial savings in vehicle weight.

**Fan-Torque Pitch Moments also from Lateral Tilting**

When using lift-fans as CMGs for air vehicle pitch control there will be a fan-torque pitching moment - in addition to the gyroscopic one - associated with their lateral tilting. But, unlike the gyroscopic moment, it will
Thrust-Vector Assistance from Longitudinal Tilting

The fan net torque, however, may in some instances be insufficient to provide this static restoration. So, to aid in this process, and to improve the vehicle’s static stability in all instances, an additional pitch control moment is normally obtained by collectively tilting the fans in the longitudinal direction while simultaneously tilting them laterally. These improvements all derive from the resulting non-vertical thrust vector, which also provides more direct horizontal motion control. Longitudinal tilting does introduce a destabilizing inertial reaction on the vehicle, however, but this can be either mitigated by proper selection of the system’s gyroscopic properties, or eliminated entirely by employing curvilinear tilt paths.

Therefore, in general, tilting of the fans for full and proper pitch control of the air vehicle will be in an oblique direction, hence the name of the control method in either of its two executions to-date: single- and dual-axis OAT.

Single-Axis Oblique Active Tilting (sOAT)

In the first and simplest method, called single-axis OAT or sOAT, the fans or propellers tilt about a fixed and oblique horizontal axis, and the corresponding tilt path lies along a vertical plane oriented at a fixed angle $\lambda$ from the longitudinal direction (Figure 11(a)). The tilt angle $\psi$ is measured along the tilt-path plane, and is zero when the propeller spin axis is vertical in the aircraft reference frame (Figure 11b).

sOAT not only provides full, helicopter-like pitch control of the vehicle, it also improves stability and control in yaw and roll either by reducing their high degree of coupling normally associated with dual-fan platforms or – depending on the circumstances – by using that coupling to advantage. This, together with its simplicity, makes sOAT the control method of choice for small air vehicles like the MicroVader.

Limitations of sOAT

Yet, for all its simplicity – or perhaps because of that simplicity – there are several shortcomings to sOAT. If there are no separate and additional means for collectively tilting the propellers forward, then – because of the fixed tilt-path plane – they will always be carried outwards in forward flight. Up to a certain point this is advantageous as it reduces the effect of pitch-up while flying forward in hover mode, but it has no merit in airplane mode itself.

Dual-Axis Oblique Active Tilting (dOAT)

The above arguments make a strong case for the use of dOAT, and indeed, this is where current development efforts are directed. The last sub-section of the theoretical analysis to follow, a brief look at $\alpha$-$\beta$ relationships for various pitch modes, represents the beginnings of such effort.

However, dOAT is not always necessary, nor even desirable in the case of very small air vehicles like the MicroVader. It is noteworthy that the dOAT-capable eVader, as yet without an onboard programmable controller or a two-independent-variable ($\alpha$ and $\beta$) algorithm for it, has so far had its best success when wired to exactly emulate the MicroVader’s sOAT – and using it’s $\lambda$ of 45 degrees. In fact, without the MicroVader as a template, the eVader would not be flying. In addition to sOAT directly enabling pitch control, this has partly to do with the accidental discovery that sOAT markedly improves the vehicle’s stability and control in roll and yaw.

So, while dOAT is a field yet to be explored and fully utilized, sOAT is – and probably will remain so for some time – the best representative execution of oblique active tilting. All the essential features of OAT for enabling stability and control can be embodied by an analysis of the much simpler single-axis version, which is carried out in the following section.

Mathematical Analysis

sOAT Equation of (Aircraft Pitching) Motion

Figure 11 is a schematic representation of a symmetric, sOAT-equipped aircraft tilting its propeller pods by the same angle in the same but opposite oblique directions $\lambda$, and the aircraft pitching due to the following moments that result, all of which will in general have a component about the aircraft pitch axis $\beta$.

- propeller gyroscopic moment $\omega \times I_p \beta$, whose vector is perpendicular to both the propeller spin axis and its tilt axis $\alpha$.
- The propellers are assumed to be rigid and otherwise unarticulated.
- the propeller net torque $Q$.
- the attitude of thrust vector $T$ in conjunction with the height $h$ of the tilt axis above the aircraft center of mass.
- propeller pod inertial – or resisting - moment $I_p \psi$.
- Only relative motion $\nu$ need be considered if the aircraft moment of inertia $I_p$ about the pitch axis $\psi$ is taken to include the inertias of the fixed and tiltable portions of the propeller pods.

Note that these moments, except for the inertial one, are positive and tend to pitch the aircraft itself in the positive (nose up) direction. In the case of the gyroscopic and torque moments this is a result of the choice of propeller spin direction, $\alpha$, $Q$ and $T$ are assumed constant and the the center of mass of the tiltable portion of a propeller pod located at a fixed point on its tilt axis $\psi$, and $I_p$ is assumed constant and independent of the propeller-pod tilt angle $\psi$.

The vehicle equation of motion in pitch, free of any externally applied moments – aerodynamic or otherwise, steady-state or transient – is then the sum of the pitch-axis momentum relationships for various pitch modes, represents the beginnings of such effort.

\[
\begin{align*}
\dot{\beta} &= \frac{1}{I_p} \left( -I_p \sin \psi \dot{\psi} + I_p \cos \psi \dot{\psi} - I_p \cos \psi \sin \psi + h \dot{\theta} \cos \theta \sin \theta \right) \\
&= \frac{1}{I_p} \left( -I_p \sin \psi \dot{\psi} + I_p \cos \psi \dot{\psi} + \left( h \cos \theta \sin \theta \right) \dot{\psi} \right) \\
&= 0
\end{align*}
\]

which is a non-linear function of propeller tilt angle $\psi$. Assuming small values for $\psi$ then $\cos \psi$ can be approximated by 1 and $\sin \psi$ by $\psi$, and (1) becomes linear and simplifies to

\[
\begin{align*}
\dot{\beta} &= I_p \sin \psi \dot{\psi} + I_p \cos \psi \dot{\psi} + \left( h \cos \theta \sin \theta \right) \dot{\psi} \\
&= 0
\end{align*}
\]