SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
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Title: Novel Cyclorotor Control System for Operation at Curtate and Prolate Advance Ratios

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3. DISCUSSION. The patentability of the cyclorotor pitching mechanism invention disclosed is being evaluated by AFMCLO/JAZ. The patent attorneys there have been contacted regarding the release of this information. It will only be released upon their approval.

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Novel Cyclorotor Control System for Operation at Curtate and Prolate Advance Ratios

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Recent research has enabled cyclorotors to exceed the power loading of traditional rotors in hovering conditions. However, until the present work, no mechanism had been developed to actuate the complicated blade kinematics necessary for efficient forward flight. A novel cyclorotor control system was designed and constructed to actuate near optimal variable pitching schedules for operation at curtate and prolate advance ratios. This mechanism implements a four degree of freedom three dimensional cam larger than the rotor radius. Altering the position of this cam enables blade motions to account for changes in advance ratio, as well as alter the pitching schedule at a particular advance ratio, to vary the magnitude and direction of thrust. Preliminary control system testing demonstrated the ability to produce and alter diverse pitching schedules for advance ratios less than 0.85. Operating challenges resulting from improper blade mass distribution and cam bearing geometry were identified and corrected.

Nomenclature

AR = advance ratio
d2 = distance between blade pitching axis and the center of the cam following bearing
r = radius of the cyclorotor
rcb = radius of the cam following bearing
V∞ = free stream velocity vector
Vr = rotation velocity vector
VT = total velocity vector
Wcam = width of the cam
Wcb = width of the cam bearing
α = angle of attack at blade quarter chord
θ = pitch of the cyclorotor
ϕ = cyclic position of the blade
Ω = rotational velocity of the cyclorotor

I. Introduction

The cycloidal rotor or cyclorotor is increasingly being pursued as an alternative to traditional propellers for a variety of applications. The cyclorotor's unique ability to generate symmetric forces at both curtate and prolate advance ratios, exploit unsteady aerodynamics, quickly manipulate both magnitude and direction of the thrust vector and operate more quietly than traditional rotors makes it an attractive propulsion mechanism for micro air vehicles (MAVs), airships, and vertical takeoff and landing (VTOL) aircraft. However, until now, cyclorotors have been impractical on aircraft as no mechanism was available to pitch the blades in the complicated manner necessary for efficient operation at all advance ratios.

A three-bladed cyclorotor is shown in Fig. 1. Cyclorotors are characterized by the rotation of blades about an axis where the span of the blades is parallel to the axis of revolution and perpendicular to the direction of flight. Forces are generated by cyclically pitching the blades as they move around the rotational axis. The manner in which the blades pitch is known as a "pitching schedule." For instance, in a hover a positive pitch on the top portion of the cycle and a negative pitch on the bottom portion would produce an upward force. By altering the pitching schedule a cyclorotor can produce thrust in any direction.

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Figure 1. A three-bladed cyclorotor.
direction perpendicular to the rotational axis regardless of the flight condition.

While cyclorotors have been used on tugboats for decades, only relatively new light weight/high strength composite materials and experimental research to improve their efficiency have begun to make them practical for aircraft. The first free flying cyclogyro flew in April of 2011 [1]. However, to date, cyclorotor research has concentrated on improving hovering efficiency [2-16] which requires only pitching schedules achievable with a simple mechanical linkage. No mechanism has been developed to actuate blade kinematics necessary for efficient forward flight.

Pitching schedule complexity results from the relative direction of flow on each blade. Similar to conventional rotors, this is determined by velocity due to rotor rotation, the free stream velocity and velocity due to inflow. The advance ratio, as shown in Eqn. 1, is the ratio of free stream velocity to the velocity due to rotation and is the driving representation of these velocity components. The forces on each blade are dependent on the angle of attack of the blade which, in turn, is determined by the relative direction of flow. Thus, the desired pitching schedule is a function of this ratio.

\[ AR = \frac{V_{\infty}}{\alpha r} \]  

Figure 2 shows snapshots of an airfoil aligned with the relative flow as it travels counterclockwise around the rotational axis of a cyclorotor at advance ratios of zero (A), one (B) and two (C). Advance ratios less than one are referred to as curtate advance ratios while those greater than one are referred to as prolate advance ratios. An advance ratio of one, wherein the velocity from rotation is equal to the free stream velocity, is a cycloid. Advance ratios near one are particularly unusual as a 180 degree blade pitching change is necessary (near the bottom of the rotation) as the blade retreats and the flow direction relative to the blade changes. The flight criterion to operate at prolate advance ratios demands that the pitch schedule of a blade needs to monotonically increase throughout the cycle of a revolution from \( \phi = 0, 2\pi, 4\pi, \ldots, m\pi \) where \( m \) is the number of revolutions. The blades would need to be pitched relative to this zero angle of attack positions to produce force in the desired direction.

Traditional control mechanisms used until now pitch the blade by attaching control rods from the blade to a rotating eccentric ring. By varying the position of this eccentric ring the blades are pitched approximately in a sinusoidal manner with variable amplitude and phase; however, this sinusoidal pitching schedule cannot efficiently compensate for increasing free stream velocities because the fraction of rotation at which the pitch of the blades can be optimized decreases with increasing advance ratio (the optimum pitch schedule becomes non-sinusoidal). Thus these mechanisms are limited to operation at low curtate advance ratios. The only wind tunnel tests performed with a sinusoidal pitching schedule indicated a poor efficiency at advance ratios approaching 0.5 [17].

Pitching schedules that more accurately account for incoming flow direction are more efficient at all advance ratios since the pitch of the blades can always be optimized. Seigel et al. performed unsteady Computational Fluid Dynamics simulations which showed that implementation of non-traditional pitching enables efficiencies comparable to pitching and heaving motions at prolate advance ratios [18]. However, no mechanism has yet been developed to produce all of the necessary pitching schedules. Suggestions have been made to use multiple cams [6] or control the blades individually [19]. However, multiple cam mechanisms are extremely complicated and only
efficient at specific advance ratios, while individual blade control by electronics or hydraulics is impractical at high rotational speeds since the large blade rotational accelerations necessary cannot be achieved with the speed and magnitude required.

II. Background and Theory

A cyclorotor control mechanism was developed to achieve the diverse pitching schedules necessary to efficiently operate at a range of curtate and prolate advance ratios. A conceptual drawing of the mechanism is shown in Fig. 3. Each blade is connected to a cam bearing which is positioned behind the axis of rotation of the blade. This cam bearing acts as a counterweight, thus moving the center of gravity behind the blade pitching axis. The centrifugal force from the rotation of the cyclorotor produces a pitching moment that forces the bearing to rest against the inside of a cam slightly larger than the rotor. At curtate advance ratios this cam bearing creates a counterclockwise pitching moment, where at prolate advance the cam bearing creates blade pitching moments in both direction depending on the position of the blade. Thus the design allows centrifugal actuation to force the cam bearing against the cam at both curtate and prolate advance ratios.

Referring to Fig. 3, the cam (1) is manufactured such that each cross section is a different shape. Translating the cam along the rotational axis (x axis) causes the cam bearing (2) to follow one of the infinite cross sectional profiles. If the cam is centered on the x axis (y = z = 0) then each cam cross sectional profile produces a base pitching schedule for a particular advance ratio (each x axis cam position corresponds to a different advance ratio). If implemented on a cyclorotor aircraft or cyclogyro, each base pitching schedule could be designed to produce the aerodynamic forces necessary for equilibrium at a particular forward speed.

These base pitching schedules can be altered in different ways for both curtate and prolate advance ratios in order to alter the magnitude and direction of the cyclorotor aerodynamic forces. At curtate advance ratios the cam may be translated along the axes perpendicular to the rotational axis (y and z axes). This produces approximately sinusoidal deviations from the base pitching schedule. If implemented on a cyclogyro, a pilot or computer would move each cyclorotor cam in the y and z direction to alter cyclorotor aerodynamic forces. This would alter aircraft thrust and lift and, if multiple rotors were used on an aircraft, could create rolling, pitching and yawing moments. Changes in incoming free stream flow can be accounted for by rotating the cam about the x axis.

At prolate advance ratios existence of 90 degree pitching angles prevents movement of the cam perpendicular to the rotational axis. However, the nature of the required pitching schedules is such that the thrust can be increased or decreased by translating the cam along the rotational axis. The direction of the thrust can be changed by rotating the cam.
The reference coordinate system is shown in Fig. 3. Cyclic blade position is measured positive counterclockwise from the positive z axis (\( \phi \)). Blade pitch is measured positive clockwise from a blade path tangent line to the chord line (\( \theta \)). Rotation of the rotor is positive counterclockwise. Any base pitching schedule can be actuated by this control system with certain limitations to the blade pitching rate (explanation follows). Base pitching schedules may be optimized to produce the forces required for numerous flight conditions. However, for this initial experiment, the cam and pitching schedule were designed such that the blades compensate for changes in advance ratio only. This pitching schedule will be referred to as the zero angle of attack pitching schedule (ZAOA).

The ZAOA pitching schedule is designed such that the neutral cam position (\( y = z = 0 \)) always produces a zero degree blade angle of attack at the quarter chord. Note that this pitching schedule will not result in zero resultant thrust. Friction on the blades and blade supporting components will create circulation in the air and the virtual camber effect (effective airfoil camber arises because curvilinear flow causes velocity to vary along the chord line) will create a resultant thrust. Each point in the pitching schedule is found by aligning the blade chord with the leading edge of the blade at the quarter chord location \( (V_T) \). This ZAOA pitch angle is a function of blade cyclic position (\( \phi \)) and advance ratio (AR). A derivation of this equation is beyond the scope of this paper.

\[
\theta(\phi, AR) = \arctan\left(\frac{AR \sin(\phi)}{AR \cos(\phi) + 1}\right)
\]

Equation 2 is plotted in Fig. 4 for different advance ratio values between zero and two. Notice that at curtate advance ratios (shown in red) the blades pitch back and forth within 90 degrees of zero pitch (negative pitches are shown as larger positive pitches) while blade pitch monotonically increases at prolate advance ratios. This causes the cam bearing to always follow the leading edge of the blade at curtate advance ratios and alternate between following and preceding the blade at prolate advance ratios. Ideally, at an advance ratio of one, a 180 degree pitch change is instantaneously required during rotation (shown in black). This pitch change indicates that a cam cannot produce an ideal pitching schedule near an advance ratio of one.

The desired pitching schedules at each discrete advance ratio and \( \phi \) value are mapped onto the discrete cross sectional shapes of the cam. Figure 5 shows shapes of a cam at several different cross sections, when designed for a ZAOA pitching schedule. At low curtate advance ratios the cam bearing can easily follow the shape of the cam. At prolate advance ratios the cam bearing follows a smooth path but must alternate between following and preceding the leading edge of the blade, as is indicated by blade pitch angles increasing above 180 degrees in Fig. 4. However at advance ratios near one the shape of the cam rapidly changes. At those advance ratios the cam must be spatially filtered so that the cam bearing does not “skip” off the cam. The cam shape must be designed such that centrifugal actuation is always sufficient to keep the cam bearing pressed against the cam. After filtering, the cam is composed of two continuous surfaces with a discontinuity corresponding to the transition between curtate and prolate advance ratios. A discussion of the equations that govern cam shape is beyond the scope of this paper.
This ZAOA pitching schedule provides an immense improvement over sinusoidal pitching schedules at non-zero advance ratios; however, it is not optimum. Ideally, each base pitching schedule would produce the forces required for that particular flight condition and movement of the cam would only produce forces to change flight conditions or compensate for changes in vehicle mass. Future analysis and experimentation will be necessary to determine optimal pitching schedules. This cam design can produce virtually any base pitching schedule simply using different cam shapes. The object of this experiment was to determine the practicality of this pitch control mechanism at curtate and prolate advance ratios and overcome any problems in initial design.

III. Experimental Set Up

An experimental set up was designed to test the novel cyclorotor control mechanism and collect data in order to compare traditional and non-traditional pitching schedules at curtate and prolate advance ratios. Figure 6 is a photograph of the experimental set up prior to installation in a section of the Air Force Academy’s south low speed wind tunnel. Painted steel columns hold the top and bottom inserts to the tunnel. These supports will be removed upon future tunnel installation. A Teknic M3411P-LN-02K motor is mounted on top of force balance which is in turn bolted into a section of acrylic glass which will become the top of the wind tunnel. A stationary shaft is pressed into this top force balance which then runs through a hole in the acrylic. This shaft supports a cam holder and movement mechanism. Two bearings inside either end of the stationary shaft hold a concentric hollow aluminum shaft. This shaft is connected directly to the motor and rotates both of the aluminum blade endplates. These endplates each contain three holes into which bearings that hold the blades are pressed. Three stereo lithography blades with carbon fiber spars run between the bearings in each of the endplates. One US Digital EM1-1-1000 rotary optical encoder is attached to each blade beneath the bottom endplate. Wires from these encoders run through the inside of the rotating aluminum shaft to a Moog EC4199 slip ring attached to a force balance on the bottom of the tunnel.

Figure 7 shows the three segments of a curtate cam. The cam was designed as a three part assembly in Solidworks then printed using Accura®
Xtreme plastic. This cam was fastened with tape into the aluminum shell. This aluminum shell is held by a series of stereolithography parts. These parts allow the cam to translate in the x, y and z directions as well as rotate about the center shaft. Threaded inserts in the plastic parts hold bolts. The cam may be moved and then secured by the bolts between each test of the rotor.

Cyclorotor blades were designed to withstand the centrifugal and aerodynamic loads, for ease of manufacture, and straightforward to integrate into the assembly. Figure 7 shows the assembled blade and cam following bearing. A series of ribs in the SLA blade shell support a NACA0015 profile that runs the length of the 25cm span. These ribs are connected to two carbon fiber spars positioned 1cm and 2cm from the leading edge of the 4cm chord. The main spar connects to an optical encoder below the lower endplate (not pictured) while the rear spar extends beyond the blade and attaches directly to the cam following bearing. Two spars were used to increase blade torsional rigidity. This bearing was initially sheathed in a nylon ring to reduce wear on the cam, but was altered to a tapered Teflon sheath after preliminary testing.

The motor was operated and all of the experimental data recorded through the electronics setup shown in figure 8. All of the electronics were be managed by LabVIEW.

As a result of the high wind tunnel demand, preliminary pitching schedule testing was performed outside the tunnel. Although different aerodynamic forces and moments were produced in this scenario, the effects should not adversely affect the pitching schedule, except at advance ratios very near to one, because the centrifugal pitching moments are two orders of magnitude greater than the aerodynamic moments. At high curate advance ratios aerodynamic dampening may decrease the

IV. Results and Discussion

Preliminary testing demonstrated the overall effectiveness of the design and identified necessary design improvements. Specifically, results show that the cam bearing shape introduces pitching error and that the original geometry could not achieve advance ratios greater than 0.7 due to mechanical interference. However, geometry modifications overcame these problems and successful operation was achieved at curate advance ratios less than 0.85.
A. Curtate Pitching Schedule Testing

One of the problems encountered in initial testing resulted from cam bearing shape. Figure 9a displays blade 1 pitch for a moderate advance ratio cam setting at different RPMs. Two ideal advance ratio curves are superimposed on the measured data. For the first half of the rotation the blade pitch follows an ideal advance ratio of 0.56 while over the second half of the blade closely follows an advance ratio of only 0.32. The difference between the ideal and measured blade pitch for each rpm is given in Fig 9b. Pitch error relative to these two different advance ratios at a fixed cam setting is always less than 5.5 degrees. Thus the blades are precisely following two different advance ratios.

This disparity in advance ratio tracking was produced by the cam bearing covering outer shape. Figure 10 shows a cross section of the cam with the same cam bearing running on opposite sides (moving out of the page on the left and into the page on the right). The lofted cam shape slopes in the same direction on both sides of the cam, however the cam bearing runs along different sides of this slope. With a square cam bearing profile this slope causes the bearing to follow different cam cross sections and therefore advance ratios at different cyclic locations. At cyclic locations less than 180 degrees the cam bearing follows a higher advance ratio as is depicted on the left hand side of Fig #. For the remainder of rotation the bearing follows a lower advance ratio as shown on the right side of the same figure. This error in blade pitch can be circumvented by making the cam bearing profile narrow to a point at the outermost surface. The cam bearing shell was replaced with a Teflon one as depicted in Fig. 11 for further testing. Note that the similarity in blade pitch with increasing rotational velocity indicates that there is adequate centrifugal actuation to pitch the blades with the current blade mass distribution up to advance ratios of 0.79. With inadequate centrifugal actuation the blades should more accurately follow the cam with increasing RPM since the relative ratio of the centrifugal actuating forces to frictional dampening forces increases.
Another problem quickly became apparent during testing. During testing at an advance ratio of approximately 0.79 a previously unnoticed squeaking sound was heard. Inspection of the rotor identified that the cam bearing shaft (extended rear spar of the blade) had sustained slight scarring damage from impacting the cam which is shown in Fig. 12. This cam and rear spar interaction caused the erratic blade motion and prevents operation of the constructed rotor with the original blade geometry at any greater advance ratio.

The identity of the cam/shaft interaction was found to be an oversight in blade and cam bearing geometry. Figure 13 shows two variations of cam bearing geometry at bearing locations corresponding to a blade pitch of 0 and -90 degrees. In Fig. 13a, the radius of the cam bearing is less than the sum of the rear shaft radius and the distance between the blade pivot point and the center of the cam bearing shaft. This was the case in the original experimental design. In Fig. 13b, the cam bearing radius is greater than the sum of those distances. The distance that the cam surface is displaced from the rotor rotational axis is dependent on the magnitude of each of these parameters. With the geometry in Fig 13a the cam shape corresponding to an advance ratio of zero coincides with the space the rear spar occupies when blade pitch approaches -90 degrees. Thus at advance ratios slightly less than one the rear spar strikes the cam at this cyclic position.

This problem can easily be alleviated by slightly altering the blade geometry. Specifically the ratio of the cam bearing radius to the sum of shaft radius and distance from blade pivot point to cam bearing center must be greater than 1. This design constraint is given in equation 3.

\[ r_{cb} > r_{cbs} + d_1 \]  

(3)

A cyclorotor configuration that meets this requirement is drawn in Fig. 13b. Only large negative pitches proximate to a cycloid advance ratio require this geometry alteration. Large positive pitches do not result in cam bearing shaft-cam interference as relative cam bearing position displaces the rear spar further from the cam surface.

![Figure 12. Rear spar damage. Only the upper damage was sustained during the test run. The lower damage was sustained during high speed photography testing.](image)

![Figure 13. Cam shaft and cam interference for different cam bearing geometries](image)

The experimental set up was modified to meet this design constraint by decreasing the distance between the rear spar and the blade pivot point from 10 mm to 7.5 mm. Changing this distance was selected over increasing the
cam bearing size due to the maximum cam holder diameter available. Thus, new blades and a cam were produced based on this change. The installed upper portion of these blades is pictured with the new cam bearings in Fig. 11.

Reevaluation of the pitching mechanism with the modified hardware demonstrated system effectiveness up to an advance ratio of 0.68. Figure 14a plots ideal and measured blade pitching motions for a single blade at 200 RPM over a full range of curtate advance ratios and Fig. 14b. plots pitching error in degrees for advance ratios less than 0.68. At those advance ratios blade pitching error is less than 6 degrees. Error in blade pitching motion is primarily due to differential advance ratio tracking with a finite cam shell area touching the cam and a slight cam tilt relative to the rotor. Positioning the cam more precisely and machining new metal cam bearing sheaths should significantly decrease the first two errors.

At advance ratios greater than 0.85, centrifugal actuation is inadequate to keep the cam bearing pressed against the cam and the blade oscillates upon encountering large negative pitch gradients. This problem was anticipated if the mass distribution of the blade which dictates centrifugal torques and blade dampening forces such as bearing friction and aerodynamics were incorrectly estimated. Spatially filtering of the cam was designed to prevent this problem, but it relied on a precise estimate of blade mass distribution and bearing dampening forces to predict blade motion over regions of large negative pitch gradients. Larger than anticipated dampening forces as well as a lack of an accurate means of determining the real blade mass distribution lead to an overestimate of the pitch gradient that the system could achieve. This problem can be easily corrected by increasing the degree to which the cam gradient is smoothed out in filtering or increasing the mass behind the axis of rotation of the blade. Further, aerodynamic dampening due attempted high advance ratio actuation at a zero advance ratio will be eliminated in the wind tunnel and the advance ratio at which the system can be precisely operated may increase.

**Figure 14. a) Ideal and measured blade kinetics for advance ratios between 0.1 and 0.95. b) Blade pitch error for advance ratios less than 0.68**

B. Future Recommendations

Thus far research this research has been concentrated on developing the mechanism to produce the spectrum of blade kinematics for cyclorotor forward flight. An in depth analysis of cyclorotor aerodynamics at forward flight speeds remains to be performed. Furthermore cams have only been produced to test the system at curtate advance ratios. A prolate cam must be constructed to evaluate this mechanism at all advance ratios.

Although the ability to produce diverse pitching schedules enables cyclorotors to operate at forward velocities, identifying the most efficient pitching motions is a challenging and essential task. Unsteady aerodynamics, curvilinear flow and varying velocities on the blade make it an aerodynamically daunting. Thus coupling a way to visualize the flow through the rotor with an iterative method may be required to isolate more efficient pitching schedules. Computational fluid dynamics (CFD) may provide the best way to accomplish this. CFD simulations have been shown to accurately predict cyclorotor thrust and torque, and thus might be employed to visualize and test many different blade motions without demanding new cam construction for each pitching schedule.
V. Conclusions

Experimentation demonstrated successful operation of a novel cyclorotor pitching mechanism at curtate advance ratios and identified several important design requirements. The difference in blade pitch between ideal blade motions and measured motions was less than 6 degrees for all advance ratios less than 0.85 after modifications had been made. This error is small enough to conclude that the system is accurately manipulating blade motion. Further improvement in cam placement and cam bearing sheath shape and material is anticipated to further decrease this error in future tests. At advance ratios greater than 0.85 the blades failed to follow the cam over large negative pitch gradients. This problem was a result of improperly estimated centrifugal and dampening forces at these large gradients. Elimination of aerodynamic dampening by performing the same test in the wind tunnel should increase the advance ratio range achievable by the mechanism. Modification of the blade mass distribution or an increase in filtering of the cam should eliminate this limitation.

Problems observed during testing identified several important pitch mechanism design requirements. To prevent mechanical interference the sum of the rear spar radius and the distance between the blade pitching axis and the cam bearing center must be less than the radius of the cam bearing. If the opposite is true the rear spar will impact the cam at high advance ratios causing permanent damage. Further, pitching error is adversely affected by the ratio of cam bearing width to cam width. Making the cam bearing sheath taper for a fine point, without causing the cam bearing sheath to damage the cam or degrade over time is essential to accurate operation. Some materials are ill suited for use as this cam bearing sheath. Specifically rubber based materials may heat up and fracture during high speed operation and Teflon wears down over time. A soft metal is recommended for future testing.

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