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Review of Historic and Modern Cyclogyro Design

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This paper summarizes the state of knowledge of cyclogyro theory and development in order to aid those working on researching and designing cyclogyros. A cyclogyro is a horizontal-axis rotary-wing aircraft. While no cyclogyros have ever been successfully flown, the concept offers an alternative to helicopters and other VTOL aircraft with several potential advantages. Research on cyclogyro development was first begun in the 1930's and at least one prototype was actually built. With the recent interest in small UAV's and the development of lightweight electric motors and batteries, interest in the cyclogyro has been renewed in the last decade. There exists a considerable void between modern works and the significant amount of research and testing was performed in the first half of the twentieth century. Many of the early reports are difficult to locate, and there is a lack of continuity between the works in this field. The goal of this work is to present an overview of the several widely varied sources in order to reduce the likeliness of redundant efforts, encourage collaboration and advancement, and help facilitate cyclogyro evaluation in light of modern materials and technologies.

I. Introduction

THE cyclogyro (alternately cyclogiro) can be defined as a horizontal-axis rotary-wing flying machine that is capable of sustained, controlled (either autonomous or piloted) flight in both vertical/hovering flight, vertical take-off and landing (VTOL), and forward flight. To date, there have been no successful cyclogyros, although the theoretical functionality of this aircraft has been independently verified numerous times by leading aerospace researchers throughout the last century. Design attempts have been made since the late 1800s, with significant research work performed in the 1930's and 40's. Research on the subject was mostly abandoned after World War II, with researchers unable to design a control mechanism suitable for the aircraft, and with the helicopter becoming the dominant VTOL platform. Interest has resurged in the last decade with several institutions world wide applying modern technology and material advancements, including the use of computational fluid dynamics (CFD) in vehicle design, which may lead to a practical prototype in the near future. There is no recorded work on cyclogyro development from 1943 to 1998. Fourteen references were found on cyclogyro research from the period 1926-1943 [1-14]. The Horizontal-Axis Rotating-Wing Aeronautical Systems (HARWAS) report of 1969 [15] listed technical references for much of that earlier work, in addition to numerous references of magazine and other non-technical articles. Twenty-two studies on cyclogyro research were published in the technical literature from 1998 through the present (2009) [16-37],

II. Overview of Cyclogyro Operation

The cyclogyro takes its name from the cycloidal path its wings trace out relative to the air during forward flight. This motion is not unlike that of winged insects and birds. **Figure 1** shows a kinematic representation of the relative blade path for various advance ratios [15]. The top diagram in Figure 1 shows the motion traced out by the blades in forward flight, demonstrating the cycloidal shape when viewed from the side. The cyclogyro's lifting and propulsive forces are generated very similarly to the aileron and elevator controls on a traditional fully articulated helicopter rotor, where cyclic control inputs vary the angle of attack of the rotor blades individually as they rotate relative to the helicopter.

For the cyclogyro, the flapping blades are oriented in a paddlewheel arrangement, and maintain a tangential angle relative to their path when there is no control input. When control input is supplied, the blades' angles relative

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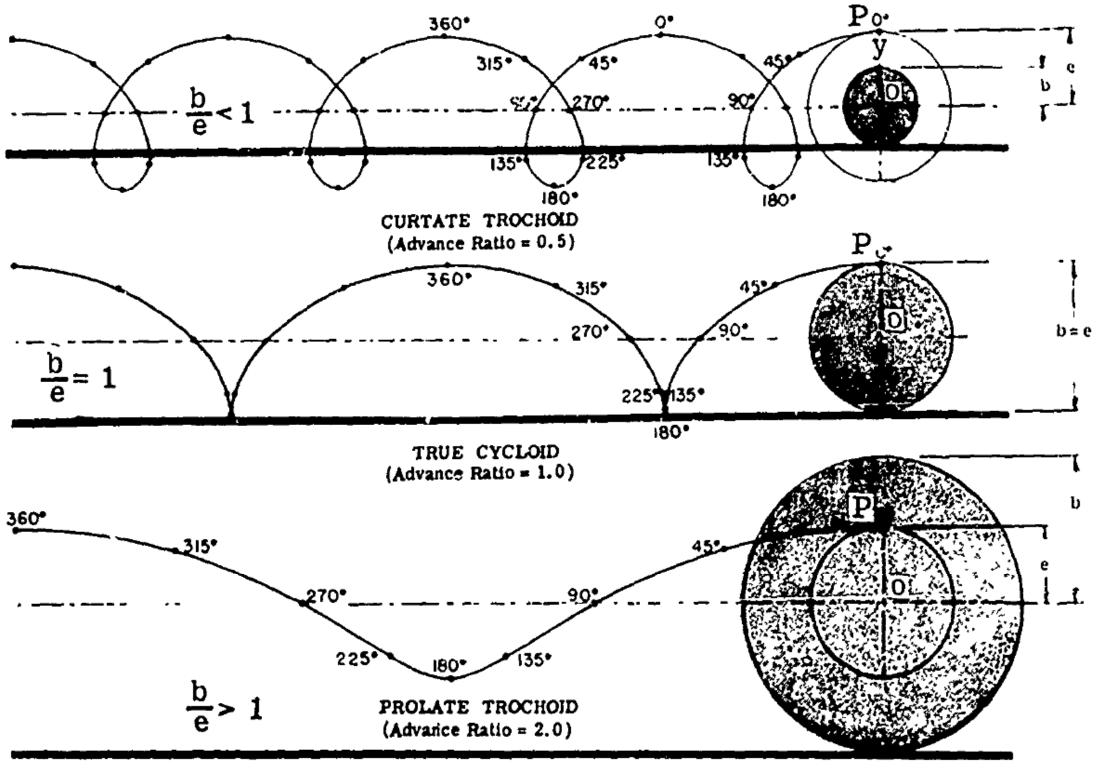

Figure 1. Kinematic Representation of Cycloidal and Trochoidal Motion. [15]

to their path oscillate with a magnitude, phase angle, and pitch offset dependent on the control mechanism. The net thrust that results is highly dependent on the design of the control mechanism and advance ratio, but in all cases it can be varied throughout 360 degrees in the plane perpendicular to the axis of rotation.

Typical aircraft configurations consist of two cycloidal rotors mounted span-wise above and ahead of the center of mass, with some form of anti-torque propulsion mounted at the rear, such as shown in **Fig 2.** Another commonly proposed variation is mounting another pair of cycloidal rotors at the rear of the aircraft instead, as in **Fig 3**.

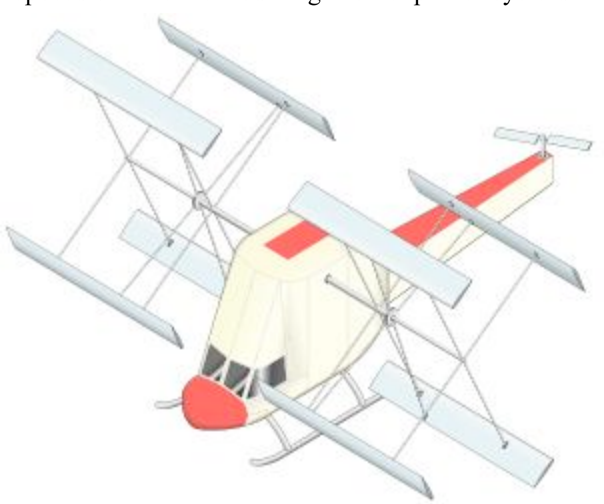

Figure 2. Artist's concept of possible cyclogyro. [38]

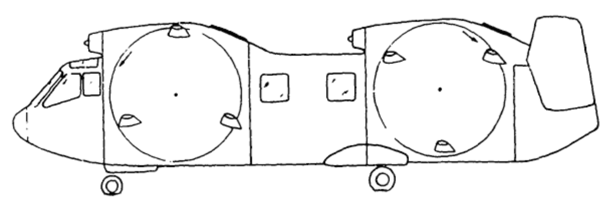

Figure 3. Design concept of possible cyclogyro. [15]

III. Overview of Cyclogyro Flight Characteristics

The cyclogyro is capable of the same flight operations as the helicopter: vertical takeoff and landing, hover, and level flight. In addition to these capabilities, the cyclogyro does not need to adjust its yaw, pitch, or roll in order to accelerate in any direction in the vertical plane that extends through its centerline [4,5,9,13,26,30,38,39]. It does require a roll maneuver in order to move laterally. All directions of motion are controlled directly by the two cycloidal rotors except for pitch, which is affected by the drive motor's torque, and must be controlled by another thrusting mechanism such as a traditional helicopter tail rotor oriented horizontally [30].

The cycloidal rotor has mathematically and experimentally been deemed capable of autorotation [4,5,9]. This phenomenon is very important to the safety of helicopter flight, and may help to ensure the safety of cyclogyro flight. When the main engine for a helicopter fails, it is possible for the aircraft to glide to a safe landing by manipulating the aerodynamic principles that cause autorotation. A rotating airfoil within a fluid stream of sufficient velocity will develop a component of the lift vector that is in the same direction as rotation and opposes drag [40]. The forward velocity of the aircraft can be used to add rotational energy to the rotor. This rotational energy can then be used to create lift to maintain control of the aircraft and slow its descent [40].

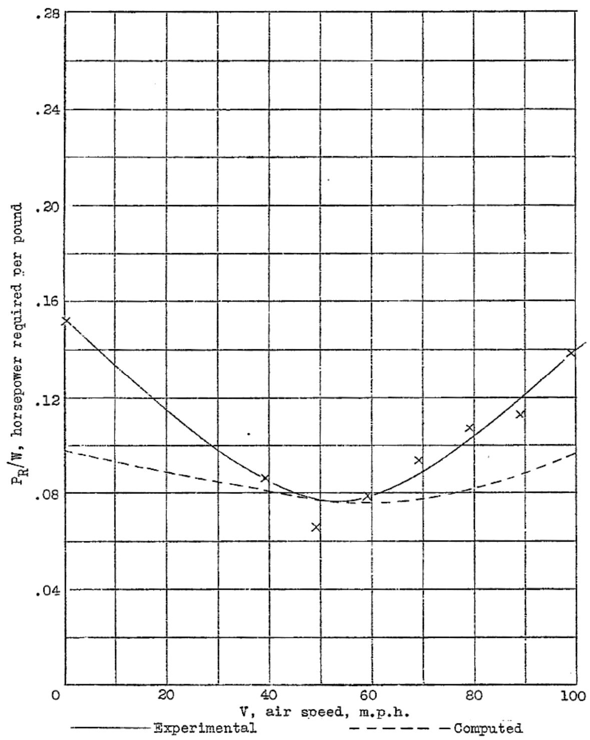

Figure 4. Power loading versus air speed. [9]

For each model of helicopter that meets FAA certification, there is a rated maximum airspeed often referred to as the "Never Exceed Velocity". This airspeed is calculated with respect to the retreating blade's relative tip speed ratio: the ratio of the rotor tip velocity to the air speed. When this tip speed ratio approaches unity, the helicopter experiences retreating blade stall, where the blade that is rotating towards the rear of the helicopter (usually on the aircraft's left side) no longer generates lift. For many commercial helicopters this maximum airspeed is very close to 150 mph [40]. Though not exactly equivalent, for a cyclogyro, this effect would be less sever, and only cause loss of lift on the top or bottom of the rotor (depending on rotation direction). Analysis and experiments performed in the 1930's documented effects that appear to support this phenomenon. **Figure 4** demonstrates early results that show the trend of increasing rotor power requirement to maintain a fixed level of thrust as a function of airspeed using both experimental and theoretical data. A variety of experiments have found an optimum air speed in the range of 50 mph for full size test rotors with airfoils similar to NACA 0012 [5,9].

IV. Overview of Cycloidal Rotor Control Mechanism

The control mechanism for a cycloidal rotor must be capable of controlling the articulation of the blades at a high frequency during high rotational speeds and radial loadings. Due to the complexity of such devices, early materials dictated very large and heavy mechanisms. Additionally, the several different classes of cyclogyro each require a unique mechanism to operate, in much the same way as different styles of an automobile engine require unique camshafts. The problem with this analogy is that automobile camshaft profiles are, for the most part, fixed and therefore a compromise between optimal profiles for different driving conditions. One of the biggest challenges facing cyclogyros is the need for a lightweight mechanism that is capable of articulating the blades optimally for the given flight conditions. A classification table that was prepared for the US Army in 1969 can be seen on the next page in **Figure 5**. The most important of these eight classes are the high pitch, "pi" pitch, and low pitch cyclogyros [15].

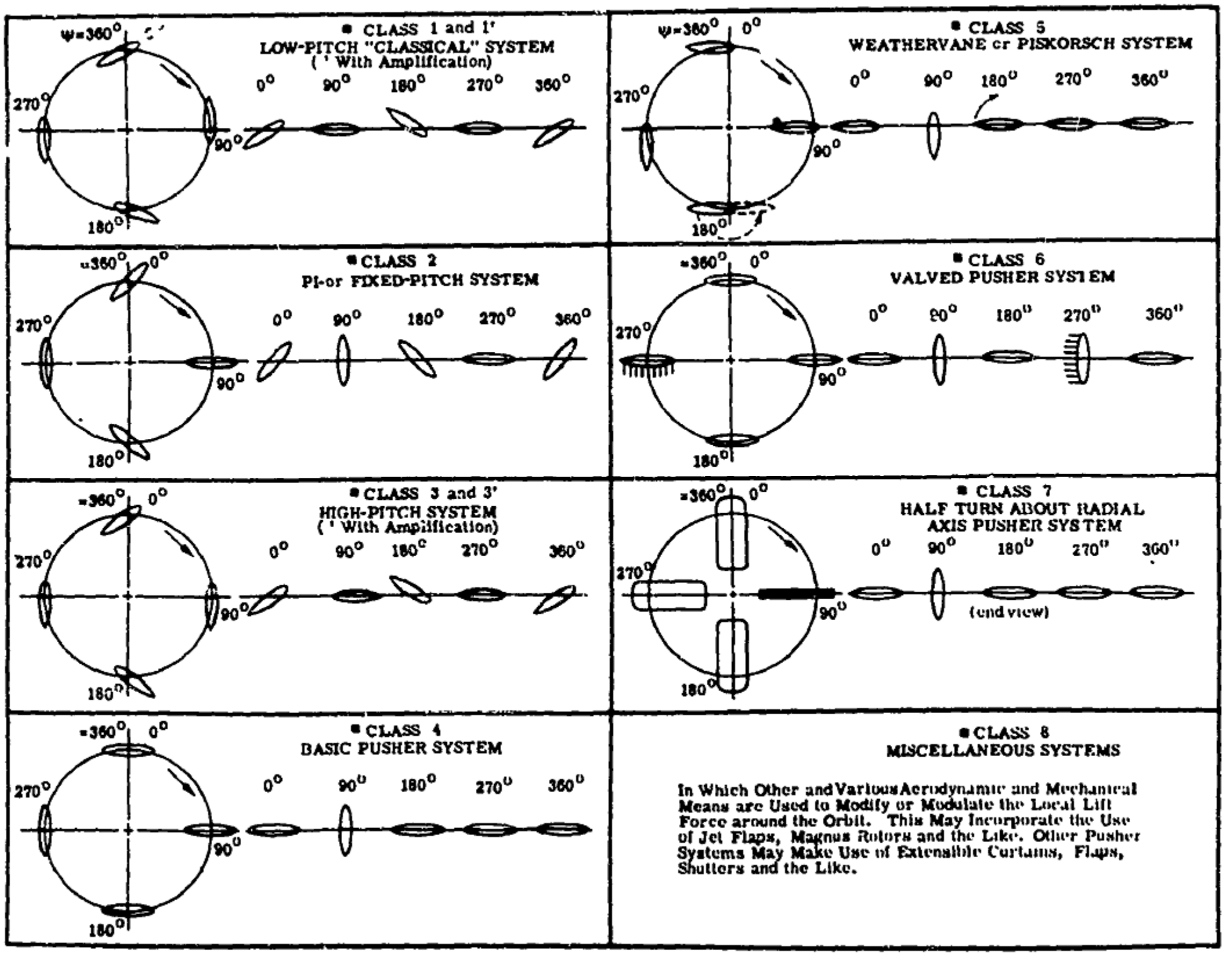

Figure 5. Cyclogyro Classification Table. [15]

Professor Kurt Kirsten from the University of Washington pioneered aeronautical cyclogyro development up until the lack of aircraft suitable materials and mechanisms lead him to develop the rotor for naval vessels. Since then, marine propulsion has achieved the greatest success to date with cycloidal rotors, and has been their only commercial domain. **Figure 6** on the next page shows a typical example of a marine cycloidal rotor produced by the Voith Schneider Company in Germany. Also on the next page, **Figure 7** shows Kirsten's original gear and cam control mechanism that many other early mechanisms were based on. The following page contains **Fig. 8**, which displays a summary of control mechanisms in 1934. Sachse [1] proposed to put Kirsten's rotors on a lighter-than-air airship and use them for propulsion instead of conventional propellers. Wheatley [6] believed based on his research that relative to a conventional airplane, cyclogyros offered superior control, maneuverability, performance, and safety at low speeds, with comparable performance at higher speeds. The main drawback of the cyclogyro compared to an airplane would be the more complex controls and difficulty in piloting.

The original "articulated paddlewheel" control ring design has been used recently by many researchers to create similar offset crank control mechanisms [4,5]. These mechanisms are still proving bulky, complex, and unable to change blade articulation schemes to match flight conditions. The most successful aeronautical design so far, by Yu et al., used a geared five bar with control ring mechanism to articulate the wings. A schematic of a similar mechanism can be seen in **Fig. 9.** The actual cyclogyro is capable of hovering while tethered and a video can be easily found online.

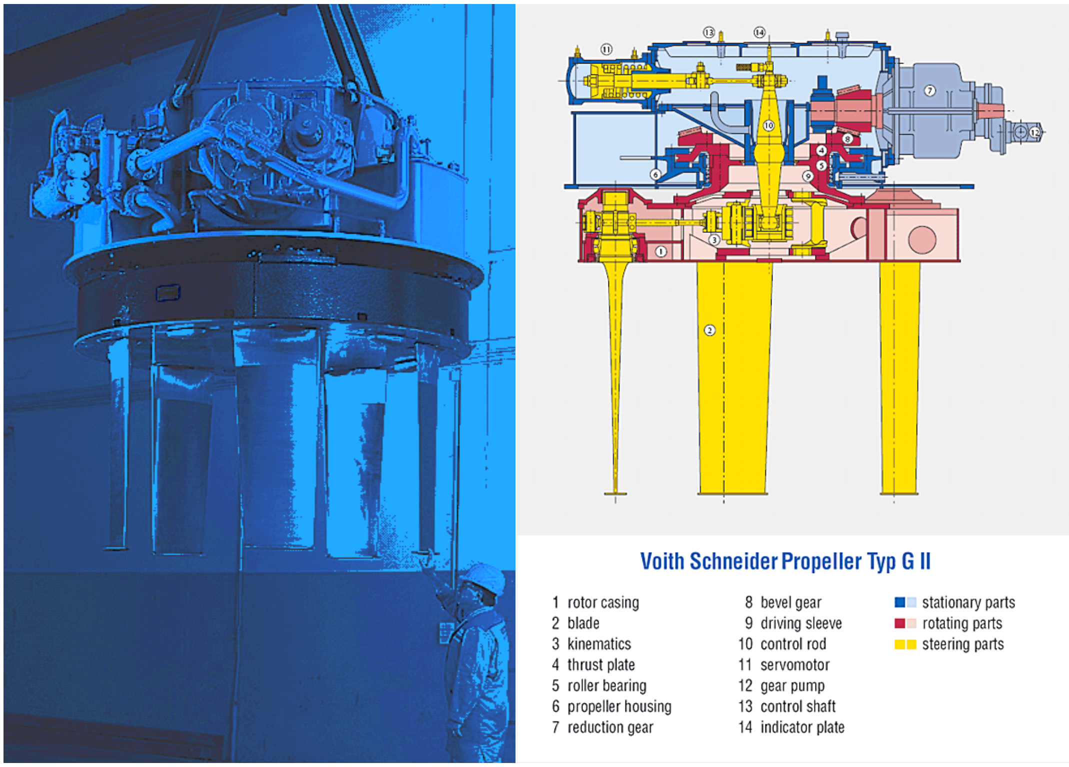

Figure 6. Voith Schneider Propeller. [44]

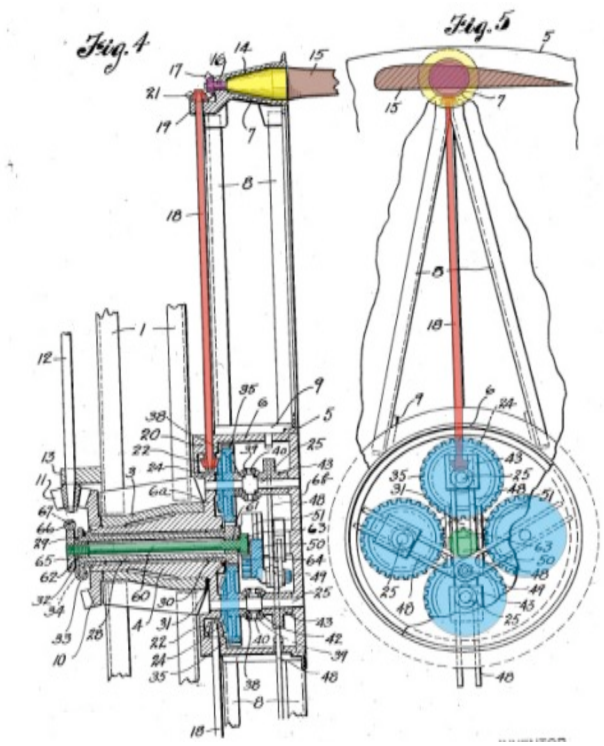

Figure 7. Control Mechanism by Kurt Kirsten (color added). [41]

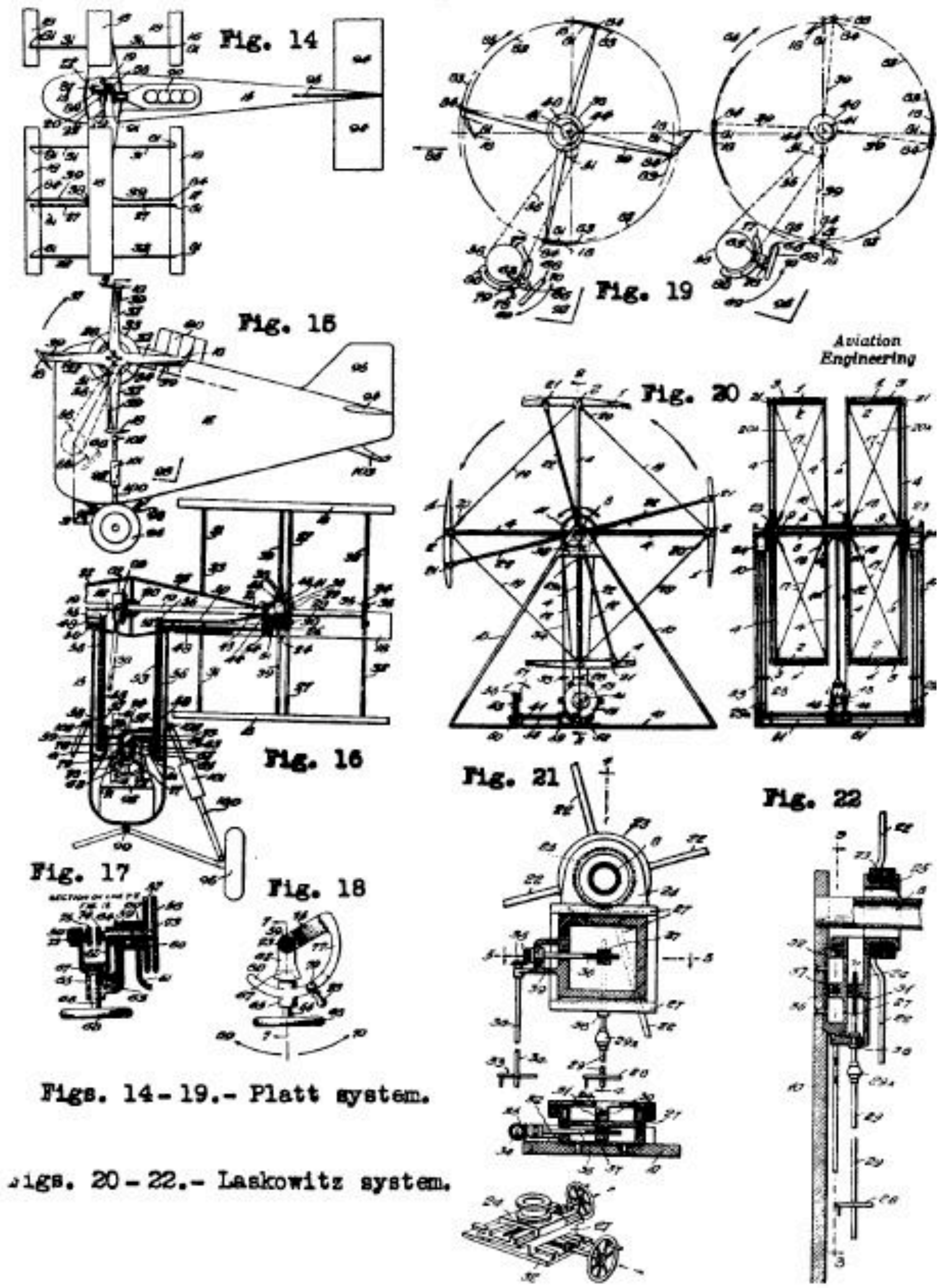

Figure 8. Survey of cycloidal propeller control mechanisms circa 1934. [13]

V. Early Cycloidal Rotor Research

In the 1933 NACA Technical Memorandum No. 727 [4], C. B. Standgren claims that his memorandum may be the first technical paper to be made public that describes the theory behind the cyclogyro in any real technical detail. Standgren's analysis describes the kinematics of blade movement for a cycloidal rotor. His observations are derived from "numerous tests made at the Institut Aerotechnique de Saint-Cyr, by means of different small-scale models constructed with the cooperation of the Office National de Inventions et de la Societe ''Expansion Franco-Scandinave' relations." He also states that the Liore and Oliver airplane company built a full scale aircraft. There is no discussion of the actual tests; rather Standgren mathematically describes the kinematics of the cycloidal rotor and the mechanism by which it generates thrust.

Standgren's version of the cycloidal propeller operates in a very similar way to the one produced today by the Voith-Schneider company. The diametrically inward surface of each blade is maintained perpendicular to an eccentric control point. Standgren also discusses the mathematical model for autorotation and shows supporting evidence for its operation during unpowered flight. Many of the models Standgren based his analysis on can be seen in **Fig. 11.**

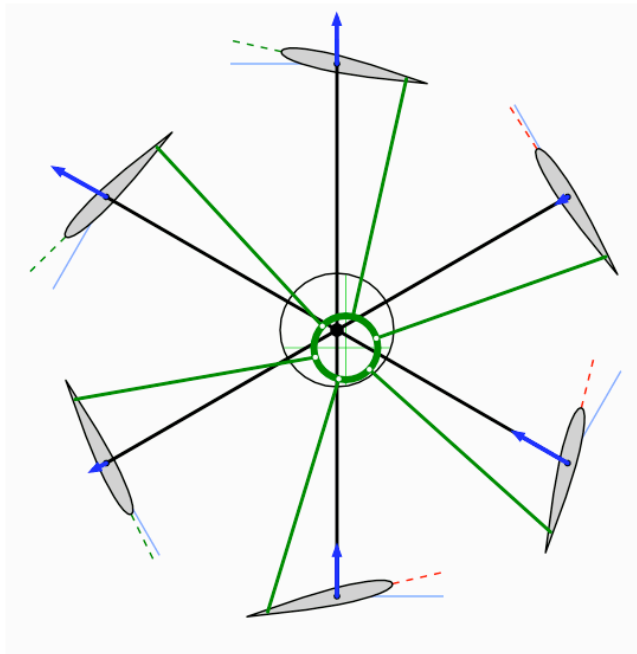

Figure 9. Geared five bar mechanism. [38]

Figure 10. Schroeder cyclogyro built in 1930. [39]

In 1934, John B. Wheatley and Ray Windley tested a rotor with 4 blades of chord 0.312 ft, and a diameter and wingspan of 8ft. The test results showed that the cyclogyro of these dimensions "would be able to ascend vertically, fly horizontally, and glide without power" [5]. This experiment showed that the "values calculated for zero rotor forces were in error" and that "the blade profile-drag coefficient was incorrectly assumed."

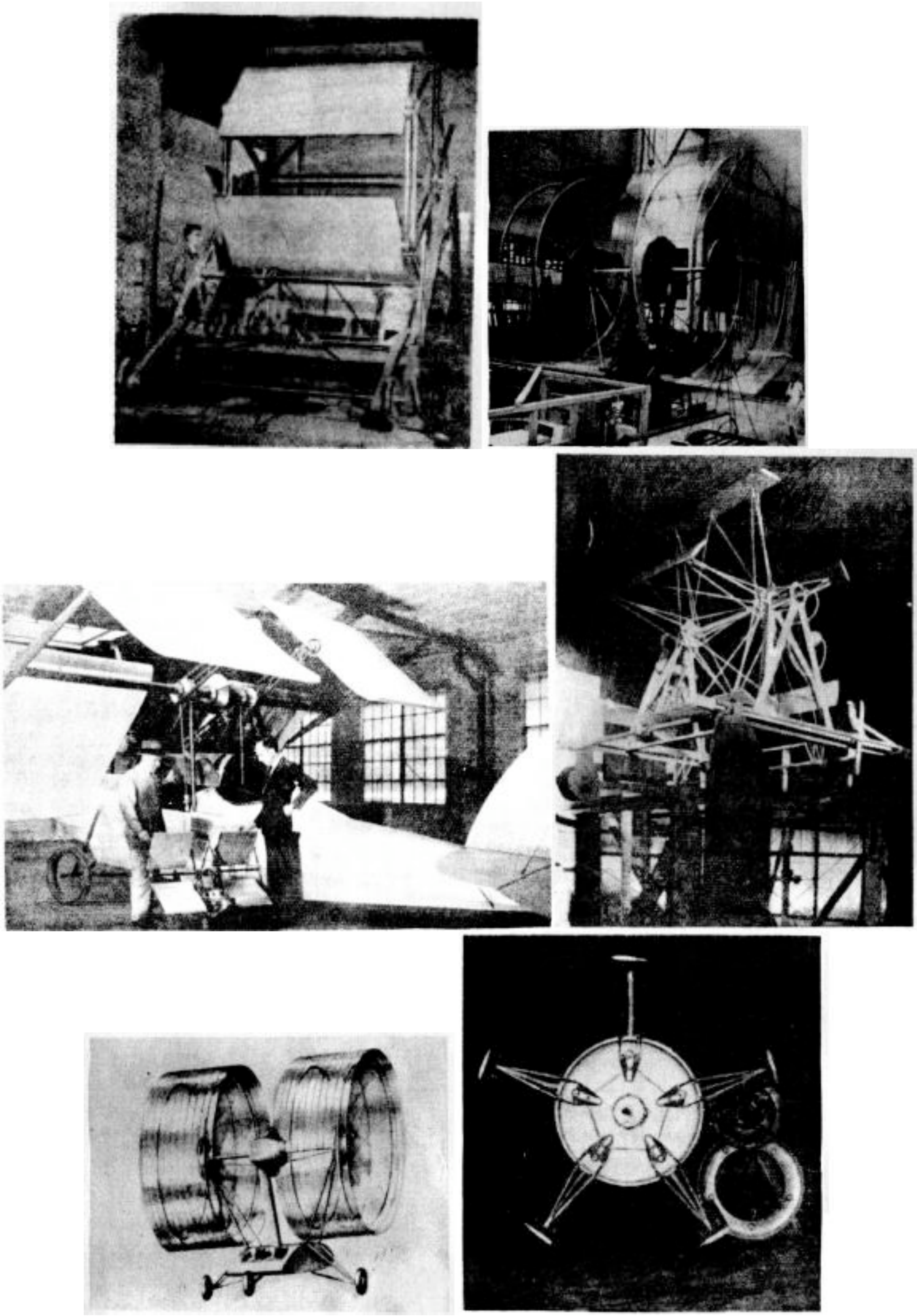

Figure 11. Standgren cyclogyro models. [4]

The drag inducing effects of an oscillating airfoil were not understood at the time of this experiment, and as the rotor's rotational speed was increased, the drag coefficient of the blade profile increased dramatically. This created the net effect of reducing the predicted performances substantially and requiring far more power than anticipated to achieve higher rotational speeds. A comparison between a cycloidal propeller and a typical airplane propeller showed that at a 100 ft/sec tip speed, the maximum lift per horsepower is 23.8 lb/hp for the cycloidal propeller and 50 lb/hp for a 10 degree pitch airplane propeller. The model used can be seen in **Fig. 14**.

Figure 12. Rahn cyclogyro airplane built in 1935. [39]

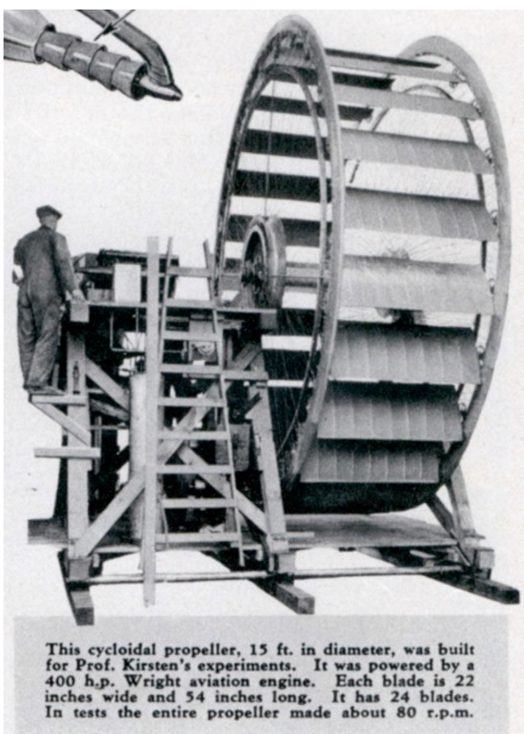

Figure 13. Kirsten paddle-wheel cyclogyro test rotor from 1935 magazine article.

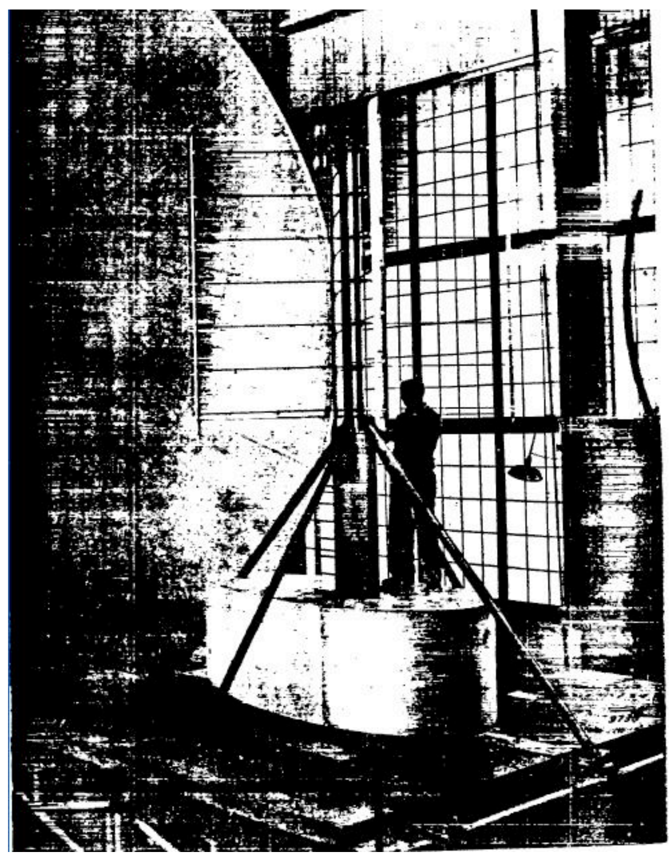

Figure 14. Test rotor from NACA Report 528. [9]

VI. Unexpected Phenomenon

The drag effect due to rapid airfoil oscillation was very little understood in the 1930's. Today, the phenomenon is well documented and of primary concern in helicopter design. When an airfoil's angle of attack is oscillating at a high enough frequency, with a high enough amplitude, it causes boundary layer separation bubbles to form on the trailing surface of the wing. The formation of these bubbles is still difficult to predict, and requires detailed experimentation and numerical analysis [40,42].

VII. Conclusion

Many modern developments have overcome the previous problems associated with creating a practical cyclogyro. Some of these very important factors include the introduction of computer aided design and manufacturing, the maturing of the commercial helicopter aerospace and RC model helicopter industries, very high power to weight ratio power plant options, sophisticated computer data acquisition and processing systems, and huge advancements in understanding oscillating airfoil behavior [15]. The main design challenges today are to integrate these systems and advancements and build upon the original research to create a practical cyclogyro. Fourteen references were found on cyclogyro research from the period 1926-1943, and twenty-two studies on cyclogyro research were published in archival journals over the last decade, in addition to work on the similar Voith-Schneider Propeller [43-46] and Giromill wind turbine [47]. In the last decade there has been a resurgence of interest in developing a practical cyclogyro aircraft. This is largely in part to the maturation of computer-integrated systems, lightweight composite materials, and powerful robust computer aided design tools. The research of cycloidal aero-propulsion in the twentieth century has been mostly fruitlessness because of limited funding, materials, technology, and creativity. Many of the resources for building small and prototype aircraft have become exceedingly affordable in recent years thanks to the recent explosion in development and sophistication of the hobbyist RC aircraft and robotics industries, as well as portable electronics, and electronic entertainment. The cyclogyro aircraft is a concept that has long been ahead of its time, but now, that time may have come. In summary, the potential benefits of a cyclogyro over a helicopter include:

- Higher forward flight speeds can be obtained because retreating blade stall is not an issue
- The tail rotor can contribute useful lift
- Less noise for quieter operation

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