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Propeller Design Requirements for Quadcopters Utilizing Variable Pitch Propellers

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***Abstract*—The use of unmanned aerial vehicles, UAV, has increases rapidly in the past several years. Now, Quadcopters, four propeller systems, are used, being designed and commercially used to allow the advantages of both flight and hovering. The basic design of their propeller blades has not evolved from the early days of manned flight. In this paper it explores the historical developments and relates to how they can use existing technology in lieu of new designs, to offer UAVs the options and efficiencies used in man flight. Furthermore, how modern materials and manufacturing techniques allows for more accurate matching of blades' needs and applications.**

***Index Terms*—Aerodynamics, blade design, efficiency and flight stability.**

I. Introduction

Any student of aviation is aware of Kitty Hawk on the 17th December, 1903, where the Wright Brothers first undertook powered man-flight. This epoch is ingrained in history now as the seminal date for what is now collectively known as Aviation and a complete new mode of transportation that has changed to world in many different ways. Less than 66 years later in the same part of the world man set-off by a rocket to walk on the moon and returned safely. Technology usually advances at rapid paces when it offers commercial possibilities, opportunities or War dictates the necessity.

The UAV market is no exception to innovation and parallels can be drawn between the start of manned flight and UAV flight. However, consider the technology available for the generation of thrust that was possible in 1903. In Fig. 1 below, is a picture taken of this first aircraft flying at what we would now call a modest height (altitude) and very low speeds [1]. Low level fight at low speeds resulted in flight instability problems as altitude and time not available for recovery and many fatalities were occurred. The success of the Wright Brothers flight was in part mainly to the sufficient thrust generated to first get if to a speed sufficient to generate lift greater than the weight, then more to achieve a height for travelling a distance.

The basic thrust was generated by a simple fixed pitch propeller made from laminate wood, see Fig. 2, below [2]. This basic design was in its infancy but sufficient for the needs of early flight.

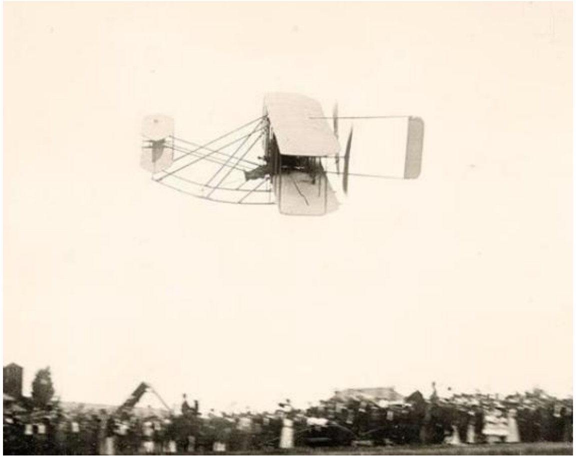

Fig. 1. Wright Brothers first aircraft.

The basic design was crude but worked, the science was not understood and the subsequent research offered more efficiencies, to be discussed later in this paper. Nevertheless, sufficient thrust was produced to accelerate the aircraft for flight [3].

Fig. 2. Wright Brothers fixed pitech twin bladed propeller.

Fig 3. Plastic fixed pitch propellers for Quadcopters.

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Considering current UAV designs, if one is designed and the propeller is sought a simple search of available commercial propellers will result in ones that are shown in Fig. 3. They may longer be made from laminated wood, but various types of plastics and composite or high carbon fibre materials. What is clearly demonstrated is that there is little difference between those used in the early days of powered flight and those now for Quadcopters [4], both are fixed pitch propellers.

These modern propellers may be waterproof and of various colours, they are however, practically identical in design and application.

Blade pitch is a critical parameter for a propeller. The pitch is in effect how much air is cut by the blade and you can liken to the gears on a manual car gearbox. The pitch set for initial acceleration (needed to take-off) but fixed and the speed in fixed blade pitch is limited by this. You could, however, set the blade pitch for maximum speed in flight. This would require a very long runway to slowly gather speed sufficient for enough lift for flight [5]. Generally, they are set at a compromise where take-off not maximized and maximum speed below that possible.

Fixed pitch designs limited the initial aircraft speeds and engineers researched the science behind the propeller thrust. The next stage in propeller development was two positioned propeller blades. Position 1 is set for take-off and position 2 for maximum cruise speed. In Fig. 4 below, is shown an example from a DC-3 that was extensively used throughout the World War II.

Fig. 4. Twin pitch propeller on a DC-3 aircraft.

Two pitch propellers allowed for optimum angle of attack, AoA, on take-off and then switch to optimum AoA on cruise. Climb and descend or other unscheduled maneuvers were always a compromise. When this became available then the flight maximum cruise speed almost doubled and large distances could be covered in half the time of fixed propellers, and equally important, with a lower fuel demand; thus longer endurance flights between refueling. At this stage the opportunities opened up for commercial transportation and ones where operators could make profits to off-set the high startup costs in aviation.

Developments have continued at rapid rates and in Fig. 5 below is an example of one of the most advanced propeller designs used [6]. This is a seven bladed and multi-geometric position, composite propeller system.

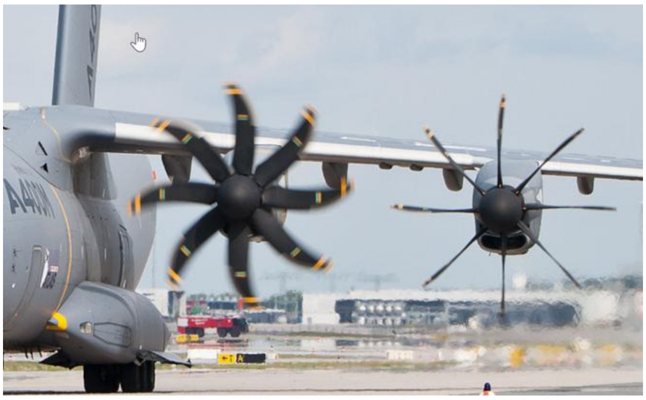

Fig. 5. Multi bladed multi-geometric bladed variable pitch.

This figure above shows the propellers in two unique positions. The right hand one is in the ‘feathered position’ and this position eliminates any load applied to the engine when not in use on the ground or if it stops working in-flight. The left hand position is in taxi idle, a low power setting whilst taxing.

II. Modern Day Variable Pitch Propellers

In the previous section the compromises that were available was discussed. In Fig. 6 below, is a graph showing how efficiency will depend on certain factors.

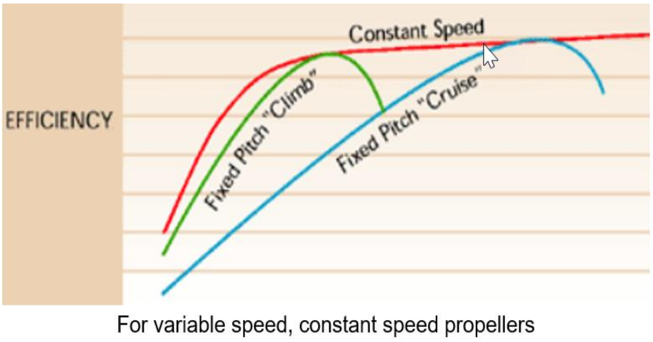

Fig. 6. Efficiency v. speed for blade positions.

When you set the pitch at a fine AoA (low angle) the acceleration is best, maximum efficiency is reached then reduces thereafter. Alternatively, when set for maximum cruise speed there is an efficiency point that beyond it drops. Loss of efficiency reduces the range, maximum take-off weight and is operating at higher rpm that produces excessive vibrations and reliability concerns to the structure of the frame.

The fixed Climb and Cruise are for propellers where the speed is increased to generate the thrust. As speed increases it approaches the speed of sound. This is not desired as the vortices and wake will generate excessive vibrations that shake the propeller and potentially it will snap due to high stress loads [7]. Modern propellers work on a constant speed system that means the maximum tip speed never approaches the higher transonic speeds where the speed of sound is exceeded. They rotate at one defined speed and power is increased by additional fuel and pitch position whilst acceleration is optimised by the blade angle set to fine. There are three principal positions and these are summarized below in Fig. 7 and are used for the main operations of take-off, cruise and start-up.

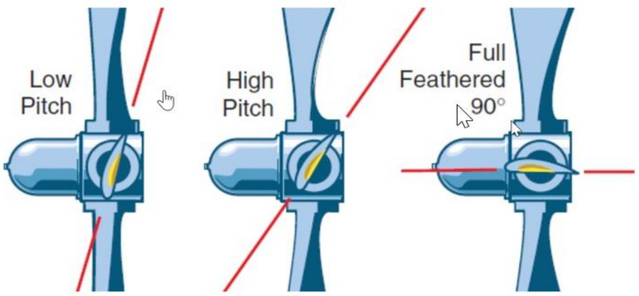

Fig. 7. Three principal positions of a variable pitch propeller.

Low pitch (also called fine pitch) is the position used for acceleration, take-off, when maximum thrust to reach take-off speed is needed. When cruise is needed the pitch is set to high pitch (also called course pitch). The third position is used for when the engine is not running, when idle after engine start-up or if the engine stops working in flight. This position will ensure no loads are applied to the engine when it rotated by external forces [8]. With the first two positions the engine power (thrust) is available to be used to suit demands, the third position is one for practical protection of the engine. For example, if the engine stopped in flight the force from the air would otherwise turn the propeller and this will result in applied loads internally on the bearing, when no pressure to lubricate.

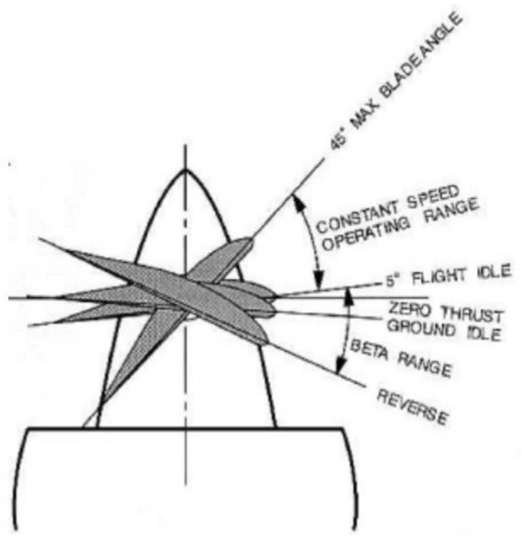

Fig. 8. Alpha and Beta positions for propellers.

There are other positions that can be selected by the pilot, these are show in Fig. 8 and include what is commonly known as Alpha and Beta positions. Alpha positions are set by the pilot in-flight to maximise the efficient use of thrust for cruise [9]. Remember that the engine is operated at a constant speed regardless of flight requirements. Alpha range is operated by the pilot with a separate level in the cockpit for in-flight, cruise, requirements. In theory there is an infinite number of positions from the lowest alpha to highest Beta value. Beta values are to set ground idle and where the AoA is below zero, thus no forward thrust and a reverse thrust generated. Reverse thrust is applied in lieu of breaking when landing and can be recongnised by the sudden increase in sound when a passenger in a turbo-prop aircraft. On float planes this affords the pilot a reversing ability to move the aircraft backwards and align for take-off, as no other way of externally pushing back in remote locations or areas. These Alpha and Beta positions offer the pilot full control over the power available and when needed. They are, in effect, the optimum for propellers and represent what is the most advanced level and operation.

Typically, nowadays, the positions can be purely dictated by the pilot or the systems can inform the pilot optimum settings for each stage of flight. In a UAV this could be automatically controlled give processing power and costs.

III. Quadcopter Pitch Positions

Quadcopters have four sets of propellers to generate the lift and movement, two clockwise and two anti-clockwise to balance the torque produced, see Fig. 9 below. As with early aircraft, increased thrust is achieved by increasing the speed. Thus, at vertical take-off the speed increases from idle to generate lift, the higher the speed the higher the lift and hence altitude [10]. To hover the speed is manually adjusted to generate lift sufficient to the load. To land the speed is reduced so the lift is less than load and the decent speed is crudely related to rate of decent. Skill and adjustment controls the UAV and when learning to operate training is needed to minimise the possibility of crashing [11].

Fig. 9. Typical Quadcopter.

Propellers on Quadcopters are smaller in diameter than most commercial aircraft applications. With propellers they are limited by the speed of sound. If a propeller has a 300 mm diameter it would need to have a rpm in excess of 39,000 to reach the speed of sound. Speed control of upper speed is considered not an operational problem when you consider maximum motor speeds are substantially below this value. Again, close examination of the blades and they are of the same design as early aircraft shown in the beginning of this paper. Fixed propeller positions are designed for acceleration (vertical take-off) or efficient horizontal movement [12]. Likewise, some may be a compromise on both. Regardless, they will not be working at their efficiency level desired

Quadcopters are powered by batteries, they have a maximum output of energy available, any inefficiency will either limit take-off load or endurance, even both [13]. It is paramount for them to be efficient to enter the next stage of commercial application.

IV. Commercial Applications

There has been a great deal of discussion on applications for UAVs other than military applications or Fire & Rescue work [14]. There are suggestions that humanitarian applications are the next step, either way, this emerging industry is still in its infancy. Somewhat like early aircraft where in War or postal deliveries in the mid-west of America.

Modern day versions of mail delivery are possible. Online deliveries from central warehouses or between central warehouses. Many might argue that use in commercial airspace is the problem, but NEXTGEN is addressing these needs and non-commercial, GA, airspace is already available. Below in Fig. 10 is a prototype Quadcopter for delivering parcels [15].

Fig. 10. Prototype parcel delivery Quadcopter.

The dropping off goods, distributing are all basic engineering problems that can be solved. Battery life is the limiting factor for application. It is paramount to use the battery efficiently. Thus, using available power efficiently for take-off and hovering even more important. As stated above, fixed pitch propellers do not allow for that and the need to use known solutions to propeller design with individual applications more critical.

In addition to battery life is stability and control. One of the most difficult problems in all flight is a controlled vertical reduction approaching landing. The landing forces are quadratic and if vertical speed doubled the force on landing is quadrupled. Given that the parcel may be delicate or sensitive to shock loads this is a problem. Currently the speed of the propellers is slowed to generate lift slightly below the load valve. The feedback to this now is visually observing. If remote then more complexities, if automatic then sensors to detect vertical speeds needed (added weight and complexity). A variable pitch propeller system offers many opportunities to control the decent at a level acceptable and controllable. For example, two rotors could be kept to generate lift for hovering while the other two apply a reverse thrust of minimum level to combine for controlled decent. There are other possibilities not addressed in this paper to apply basic aerodynamics to find solutions for all movement needs.

V. Propeller Speeds

Early fight speeds were slow buy any yardstick, the Wright Brothers Flyer 1 had a maximum speed of 30mph and even those in the First World War (Sopwith Camel) just broke the 100 mph barrier. These were all fixed pitch propellers, below in Fig. 11 is a graph showing how speeds increased during the early years.

From 1903 until the end of the First World War speeds increased very little and remained about 120 mph through most of the 1920s. The Boeing 247 when first introduced had a cruise speed of approximately 140 mph, fast by those times. The subsequent B 247D model introduced the one of the first variable pitch propeller and achieved cruise speeds in excess of 180 mph and even reaching 210 mph.

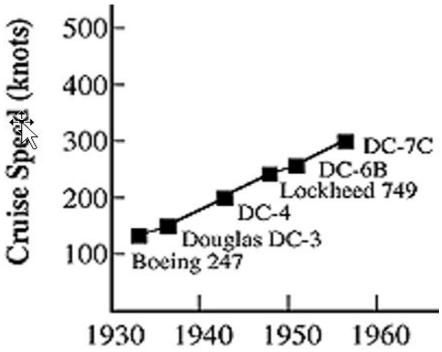

Fig. 11. Aircraft speeds in the early days of propellers.

The increase in speed became important and as engines become more powerful and efficient the ranges increased substantially. The DC 7 when first introduced, see Fig. 12 below, reached over 300 mph, with development the cruise speed was over 350 mph and reached 400 mph with a range of 5000 miles.

Fig. 12. DC 7C.

There were four engines with variable pitch propellers and the maximum speeds achieved were only superceded with the advent of the jet engines used for the De Havilland Comet and B 707. The speeds achieved with this design and configeration are simi;ar to modern Turbojet aircrafts, e.g., Dash-8.

Propellers have reached close to the maximum epecations now, they are more efficient for flights in the 20.000 ft altitude and relatively shorter distances with Turboprop engines. The theory of propellers is extensive and substatntially more advances than the first fixed pitch ones used up to the early 1920s or thos on simple general private aviation ones now.

VI. UAV Expected Requirements

UAVs are now operated remotely by controls that are either within the visual line of flight, VLS, or outside the visual line of flight, OVLS. There are two principal aspects to be addressed. First, the efficient use of battery power and secondly by having more control in vertical accent and decent. This paper proposes the use of variable pitch propellers to address these two aspects [16]. Fig. 13, below is shown the real aim of the next generation of Quadcopters where products are delivered from source to end user.

Fig. 13. Quadcopter – the desired next generation.

Current variable pitch propellers have their speed controlled by a mechanical/hydraulic governor that stops over run and also underrun. A UAV will need electronic governance of each of the four propeller blades. This paper does not address control systems for this level of detail. Nevertheless, the situation is that the aerodynamic theory and application does exist and it is not required to start from nothing to building the possibilities. In the name of the great Soichiro Honda (1906-1991) ADOPT, ADAPT and IMPROVE. This can be the principal to take UAV Quadcopters to their next level of usage. There are implications, for example, an Alpha and Beta level on the remote or automatic system [17].

VII. Next Stages of Research

To achieve these requirements several stages are needing research and solutions identified. Variable pitch blades that can be controlled electronically, speed governors are too complex and heavy, and an electronic solution similar to hard drive speeds in computers. Variable pitch blades designed to suit applications, e.g., speed, payload that are aerodynamics clarified for variable pitch quadcopters blades. Finally, evaluating how we can design a quadcopter to incorporate.

VIII. Future Research

Research will follow a core direction and can be divided accordingly: Aerodynamics of small variable pitch blades; blade design evaluations; and electronic controls for constant speed and sync as in multi-propeller aircraft

Aerodynamics of blade design is with low Reynolds numbers and the influence of bend and twist on them during changing pitches. They will be flexible, but how much strength is needed must be established.

Material strengths and blade design, including manufacture to ensure rigidity but lightweight. Composites and thermosetting plastics are the main materials being researched.

Finally, constant speed control is a separate research project between the lead author and a different group of researcher.

IX. Conclusion

Aeronautical engineering has constantly faced design challenges to improve efficiencies and operational usages. Propellers are no exception and the development of variable pitch propellers have been clarified with their applications. Quadcopters have parallels in their development and by benchmarking to areas there are already solutions that only need adapting to be a solution. If UAV Quadcopters are to be used at the next level of application, then maximizing their efficiency is critical. Constant speed propellers with variable pitches will increase take-off loads, range, flight and landing stability.

Acknowledgment

This feasibility study was developed and encouraged by users and practitioners of UAV Quadcopters and we would like to thank personally Dr. B Terwilliger for his insight and recommendations to make this a seminal work. The authors are aerodynamicists and a mathematician. There next stage is to model the stability and power requirements for constant speed blades used with Quadcopters.

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