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STUDY OF PROPELLER DESIGN PARAMETERS

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ABSTRACT

In this paper, Propeller design parameters and propeller testing methods are presented. The propeller manufacturers are trying to increase the delivered power and the system diameter of the propellers to meet all requirements. This has led to a higher power density of the propeller and to a greater risk of cavitation. That is why the design process is complex and has to rely on calculations and model tests. Computer Aided drafting programs Solid Works are mostly used for entire design procedure of propeller, from aerofoil selection to final part generation. QMIL and QPROP were the programs of choice for producing a propeller design to obtain minimum losses and proper aerodynamic efficiency. To obtain the effect of fuselage blanketing on propeller performance, wind tunnel tests were conducted. The propellers will be constructed out of windsurfing masts, high density foam, and fibreglass.

INTRODUCTION

A propeller is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the airfoil-shaped blade, and a fluid (such as air or water) is accelerated behind the blade. Propeller dynamics can be modeled by both Bernoulli's principle and Newton's third law. Propulsion is the science of designing an engine to propel a vehicle forward or up. For aviation, propulsion is generally broken into two categories: air-breathing propulsion for airplanes and rocket propulsion for spacecraft. Both work on the principle of pushing high velocity exhaust gases out the back end (reaction thrust principle), but they differ in one significant detail. An air-breathing engine uses the air stream in which the airplane is flying to augment the propulsive abilities of the engine so it can carry less fuel. A rocket engine travels in space where there is no air, and therefore it must carry all its fuel internally. An air-breathing engine will have both an inlet and an exit, while the rocket will be closed in the front and only have an exit. In general, an air-breathing engine will get more thrust for less fuel than a rocket.

MEASURING THE GEOMETRY OF PROPELLERS USING A PITCH GAUGE

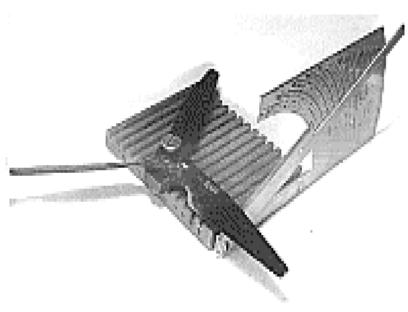

Fig. 1Commercial propeller measuring gauge

The jig is specially designed for pitch measurements of propellers at different radial sections and the pitch can be read directly from its scales without further calculations. A drawback of the gauge is the fact, that the angle of the lower side of the section is measured, which is not exactly the aerodynamically relevant blade angle. If the relative thickness of all aerofoil sections are the same along the radius and if all airfoils would have a flat lower side, then the error would simply be a constant offset from the nominal pitch angles.

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TRACING THE EDGES

A relatively simple way to get the propeller geometry with medium accuracy is the non-destructive tracing method. Attach the propeller to a block so that its axis is perpendicular to aflat table. Now prepare some pieces of flexible cardboard, slightly longer than the propeller radius. Then use a water soluble felt tip pen and paint the leading edge of the propeller.

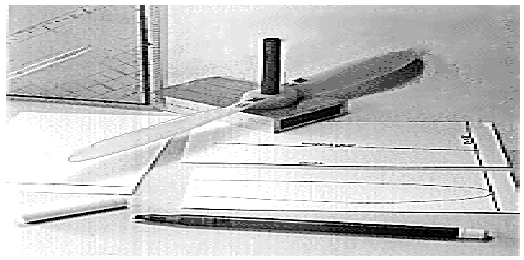

Fig. 2Tracing method and its tools

Quickly place a cardboard sheet vertical on the table and press it against the edge of the propeller, before the felt tip colour has dried. Doing the same at the trailing edge leaves you with two traces on the cardboard. Finally, you need a graph of the platform of the prop, which is easily created by holding the third cardboard sheet against the lower side and by tracing the outline of the blade on the board with a pencil.

The calculation procedure is as follows.

- measure the local chord length c from the planform graph,
- measure the distance between cardboard edge and leading edge trace)the height of the leading edge trace above ground) hl,
- measure the height of the trailing edge trace above ground ht,
- calculate the difference dh = hl - ht and,
- calculate the blade angle $ß = \sin^{-1}(dh/c)$

SLICING THE PROPELLER

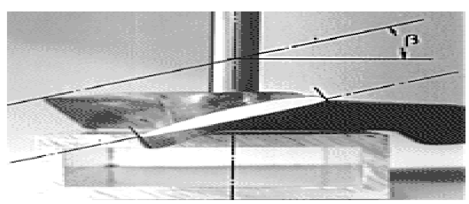

Fig. 3 Photograph of a cut through a three bladed propeller

Unfortunately an almost perfect method to measure the geometry of a propeller is destructive. The method is very simple: beginning at the tip, we cut a sample propeller at the radial station of interest, paint the cut white and take a photograph, including a pin in the axis of the propeller. A paper print or a slide can be used to measure the blade angle ß with respect to the axis as well as the airfoil shape or at least the maximum thickness and the camber.

USING TEMPLATES

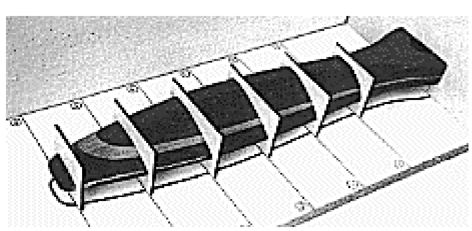

Fig. 4 Propeller blade for an ultra-light airplane & the matching set of templates

This method is very similar to the slicing method, but instead of cutting the propeller into pieces, small, flat templates are used, which are attached to the waxed surface of the propeller using quick setting polyester putty. These templates can then be photographed and dealt with as with the slicing method. The templates are made from plywood and should resemble the propeller section closely, leaving a small gap of about 2 mm only, which will be closed by the filler. They are made in two parts, so that they can be separated into an upper and a lower segment - the lower part must fit flush to the table to have a reference for the blade angle.

THRUST, POWER AND EFFICIENCY

The Thrustof a propeller depends on the volume of air (or water) accelerated per time unit, on the amount of the acceleration, and on the density of the medium. Based on momentum considerations, it can be expressed by the following formula:

$$T = \frac{\pi}{4} \cdot D^2 \cdot \left(v + \frac{\Delta v}{2}\right) \cdot \rho \cdot \Delta v \quad (1)$$

Where, T = Thrust. (N)
D = Propeller diameter. (m)
v = Velocity of incoming flow. (m/s)
Δ v= Additional velocity, acceleration by propeller. (m/s)
ρ = Density of fluid. (kg/m^3)

Examining the quite simple formula reveals, that the thrust T increases when the diameter D increases (the first term is the area of the propeller "disk") or when the density ρ of the medium increases. The acceleration Δv of a propeller depends on the velocity v, thus it is generally not true that increasing the velocity v increases the thrust. But it can be said, that increasing the additional velocity Δv, increases the thrust. For a propeller of a fixed diameter, working in a certain medium at a certain speed, thrust depends on the velocity increase Δv only.

Power is defined as work done per unit time. Using the available thrust Tto drive a vehicle at a certain speed v (which already is distance per time) we can calculate the propulsive power(sometimes also called available power) from:

$$P_a = T \cdot v \quad (2)$$

Efficiency of a propeller is defined as the ratio of available powerto the engine power, which is

$$\eta = \frac{P_a}{P_{engine}} = \frac{T \cdot v}{P_{engine}} \quad (3)$$

Note, that this definition for efficiency contains the velocity v, which means, that the efficiency approaches zero as the flight speed goes to zero, because the thrust cannot become infinitely large. So this definition is not useful for the special case of static thrust. Neglecting rotational losses, the power absorbed by the propeller can also be expressed by,

$$P_{engine} = T \cdot \left(v + \frac{\Delta v}{2}\right), \quad (4)$$

Which can be used to combine the equations above into a relation between the velocity and the efficiency for a given power and diameter,

$$v = \eta \cdot \left(\frac{2 \cdot P}{\pi \cdot \rho \cdot D^2 (1-\eta)}\right)^{\frac{1}{3}} \quad (5)$$

For a given power P, it is always desirable to use the largest possible propeller diameter D, which may be limited by mechanical restrictions (landing gear height) or aerodynamic constraints.

DESIGN PRINCIPLES OF A PROPELLER

Based on the theory of the optimum propeller (as developed by Betz, Prandtl, Glauert), only a small number of design parameters must be specified. These are the number of blades B, the axial velocity v of the flow (flight speed or boat speed), the diameter D of the propeller, lift and drag distributions of a propeller and the density, ρ, of the medium.

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THE NUMBER OF BLADES

The number of blades has a small effect on the efficiency. Usually a propeller with more blades will perform slightly better, as it distributes its power and thrust more evenly in its wake.

THE VELOCITY

The velocity of the incoming fluid together with the velocity of rotation (r.p.m.) determines the pitch distribution of the propeller. Large pitch propellers may have a good efficiency in their design point, but may run into trouble when the have to operate at axial velocity. In this case, the blades tend to stall.

THE DIAMETER

The propeller diameter has a big impact on performance. Usually a larger propeller will have a higher efficiency, as it catches more incoming fluid and distributes its power and thrust on a larger fluid volume.

LIFT AND DRAG DISTRIBUTIONS

The distribution of C_L and C_D along the radius can be examined by performing an analysis for the design point. For maximum performance, the airfoils must operate at maximum L/D. However, if the propeller should also work reasonably good conditions, it is usually necessary to use a lower angle of attack for the design.

THE FLUID DENSITY

The density of the fluid has no influence on the efficiency of a propeller, but strongly affects its size and shape. As the forces and the power are directly proportional to the fluid density, a hydro-propeller will have much smaller dimensions than a propeller working in air. The same is true for high-speed tips of aircraft propellers, where instead of cavitation, but supersonic regions may occur if the pressure gets too low. Therefore, the tip sections of propellers operating at Mach numbers above 0.7 should be designed to operate at small lift coefficients below 0.5 too.

PROPELLER DESIGN PARAMETERS

In propeller blade is an important part, which is simply a rotating airfoil, similar to airplane wing, which produces lift and drag. It has both induced upwash and downwash due to the complex helical trailing vortices that it generates. The two most important performance parameters of a propeller for design and analysis projects such as this are torque and thrust it produces.

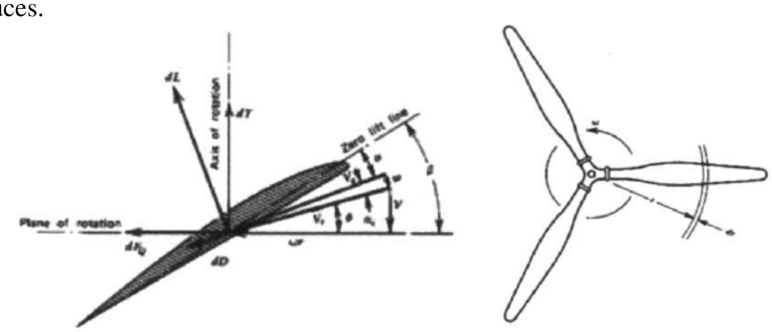

Fig. 5Propeller blade cross-section

The thrust (T) and torque (Q) generated by propeller blade can be represented as:

$$dT = dL\cos(\phi + \alpha_i) - dD\sin(\phi + \alpha_i) \quad (6)$$

$$dQ = r[dL\sin(\phi + \alpha_i) + dD\cos(\phi + \alpha_i)] \quad (7)$$

$$dL = 1/2\,\rho\, V_e^2 c C_l d \quad (8)$$

$$dD = 1/2\,\rho\, V_e^2 c C_d dr \quad (9)$$

For propeller design point of view following input variables are need to be define,

- **DIAMETER** – For different rpm propeller diameter should be vary by keeping spinner diameter constant.
- **SPEED OF ROTATION** – The speed of rotation being varied from 40[1/min] to 200[1/min] for each of the diameters.
- **VELOCITY** – The propeller is optimized for a wind velocity of about 8m/sec being expected to be about 18 mph on a normal day at the testing station as mentioned as one of the design constraints.
- Number of blades requirement.

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- **ANGLE OF ATTACK –**

$$\beta = \frac{C_L}{2\pi} \quad (10)$$

Where, C_L = Lift coefficient & has values depends on different pitch angles as shown in fig. 11.

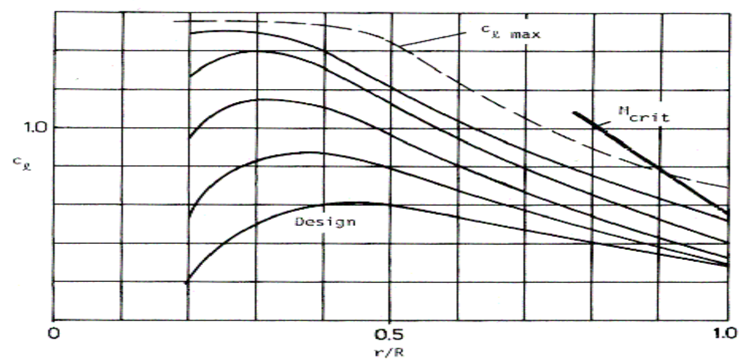

Fig.6 Lift coefficient on the propeller blade for various pitch angles

- Total angle of inclination of the blade,

$$\varepsilon = \beta + \delta \quad (11)$$

Where, δ = Blade angle.

Chordal length of the blade is,

$$b = \frac{8\pi mr}{iC_L} \quad (12)$$

Where, i = Number of blades of propeller.
m = Constant & given as:

$$m = \frac{\sin\delta\left(\tan\delta - \frac{V}{U}\right)}{\left(1 + \frac{V}{U}\right)} \quad (13)$$

V & U are the components of absolute velocity, the standard correlation is,

$$\frac{V}{U} = \frac{1}{1.2} * \frac{v}{u} \quad (14)$$

Where, v = Velocity component parallel to the axis of propeller.
u = Velocity component perpendicular to the axis of propeller.

Then, $\frac{v}{u} = \tan\delta$

PROPELLER MATERIALS

Following materials are used for manufacturing of propellers:

- **ALUMINUM:** Aluminum has a tensile strength of up to 40,000 psi, and is by far the most popular material used for outboards and stern drive recreational boat propellers. It is inexpensive, has good strength and is easily repaired.
- **STAINLESS STEEL**: Stainless steel has a tensile strength of up to 80,000 lb. psi. and is the strongest and most durable of materials used for outboard and stern drive propellers. Stainless Steel propellers can be

made thinner for better efficiency. The repair cost of stainless steel propellers is approximately double the cost of the same propeller made of aluminum.

- **PLASTIC & COMPOSITE MATERIAL**: Plastic and composite material propellers flex considerably under high loads and cannot be repaired if damaged, but they are good on trolling motors and low horsepower outboards.
- **MANGANESE BRONZE**: Manganese bronze has a tensile strength of up to 65,000 lb. psi and is used on inboard boats of up to moderate horsepower. Manganese bronze propellers are reasonably priced and repairable. Manganese bronze propellers can cause corrosion on aluminum surfaces if used in salt water.
- **CAST COPPER ALLOYS**: These materials are used when propellers are manufactured by casting process. Casting shall be performed in dry moulds using degassed liquid metal. The casting process shall be supervised in order to prevent eddies occurring. Special devices or procedures shall be in place to ensure that no slag can enter the mould.The commonly used standard cast copper alloys for propellers are subdivided into the grades CU1, CU2, CU3 and CU4 depending on their chemical composition as shown in Table 1

Table 1

Casting grade	**Chemical composition [%]**							
	Cu	**Al**	**Mn**	**Zn**	**Fe**	**Ni**	**Sn**	**Pb**
CU1	52-62	0.5-3.0	0.5-4.0	35-40	0.5-2.5	Max 1.0	0.1-1.5	Max 0.5
CU2	50-57	0.5-2.0	1.0-4.0	33-38	0.5-2.5	3.0-8.0	Max 1.5	Max 0.5
CU3	77-82	7.0-11.0	0.5-4.0	Max 1.0	2.0-6.0	3.0-6.0	Max 0.1	Max 0.03
CU4	70-80	6.5-9.0	8.0-20.0	Max 6.0	2.0-5.0	1.5-3.0	Max 1.0	Max 0.05

- **STAINLESS CAST STEEL ALLOY**: The chemical composition of the commonly used standard cast alloys for propellers made of stainless steels is shown in Table 2.

Table 2

Alloy type	**Chemical composition [%]**							
	C max	**Si max**	**Mn**	**P max**	**S max**	**Cr**	**Mo**	**Ni**
12Cr1Ni	0.10	0.40	0.50-0.80	0.030	0.020	11.50-12.50	0.50-1.00	0.80-1.50
13Cr4Ni	0.06	1.0	Max 1.0	0.035	0.025	12.00-13.50	0.50-1.00	3.50-5.00
16Cr5Ni	0.06	0.80	Max 1.0	0.035	0.025	15.00-17.00	0.70-1.50	4.00-6.00
19Cr11Ni[2]	0.07	1.50	Max 1.5	0.040	0.030	18.00-20.00	2.00-2.50	9.0-12.0

CONCLUSION

In this paper, study of Propeller Design parameters, materials for propellers, propeller testing methods are discussed. Propeller dynamics can be modelled by both Bernoulli's principle and Newton's third law. It works on the theory of propulsion. Propulsion is the science of designing an engine to propel a vehicle forward or up.The losses in efficiency are always small for a propeller of optimum design. Knowledge of the distribution of thrust and torque along the propeller performance is acquired.

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