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Design Parameters and Manufacturing Methods of Marine Propellers for Increased Efficiency in Ship Propulsion

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ABSTRACT
A propeller is a fan like device consisting of a central hub with foil like blades attached radially to it. It receives power that is generated and transmitted by the engine of the ship via a shaft mechanism and in turn, converts this power into rotational motion for the blades. These blades impart a thrust force that transmits momentum to the water and drives the ship forward. The design of these propellers and their methods of manufacture ultimately determine their overall efficiency. This report reviews and emphasizes on the factors that contribute to increase this efficiency.

Keywords - Blade design, efficiency, hydrodynamics, manufacture, propulsion

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I. INTRODUCTION

A propeller forms the basis of a propulsion mechanism which is used to drive forward a ship or marine device in a water medium. Using the principles of Hydrodynamics, the torque, horsepower, speed and fuel consumption of the ship engine are determined which primarily depend on the efficient propulsion provided by the propellers.

Attached at the hull of the ship, these fan like devices consist of a central hub around which these blades are attached through fillets.

The hub is generally given a small diameter for increasing efficiency but this could also lead to reduction of its strength. Hence, a viable diameter is allotted to it, keeping efficiency and mechanical strength in mind. Similarly, many parameters like the number of blades attached, size of the blades, materials used in its production, wake region and hydrodynamic cavitation of the blades can be optimized in design to increase efficiency, while ensuring that strength, durability and other mechanical properties aren’t compromised upon.

The design process is often referred to as “inverse” as the efficient performance traces back to the very start of the propeller design.[1] The geometric parameters and subsequent modelling of the blades have large impacts on the overall performance of the propellers.

1.1 Effect of Manufacturing Methods on Efficient Propulsion

Through the progressively changing shapes and styles of propellers, there hasn’t been much of a change in their manufacturing methods. The traditional methods like sand casting are used due to their economical approach and less requirement of skilled labor.

However, these methods lead to problems like rough surface finish, which can lead to increased surface friction in addition to frictional drag provided by the water and decrease in overall efficiency. This rough surface also prompts living microorganisms to start residing on it, thus leading to corrosion and subsequent reduction in the lifespan of the propeller.

II. FACTORS TO CONSIDER DURING PROPELLER DESIGN

The initial steps in designing a ship propeller consist of choosing the material, listing down the various parts involved in making of the device, assigning the required dimensions to these parts and ultimately, making changes and adding innovative inputs that would counter the weaknesses and negative forces such as frictional drag and unwanted turbulence.

There are two main aspects to consider during this design process. They are the geometrical parameters and miscellaneous parameters.

2.1 Geometrical Parameters include:

1. Propeller diameter
2. Speed (rpm)

3. Torque
4. Blade surface area
5. Blade outline
6. Pitch/Diameter Ratio
7. Angle of attack
8. Camber

2.1.1 Propeller Diameter:

The diameter of the propeller is related to the efficiency. Lesser the diameter, more is the amount of power transmitted to the hub for rotational motion. It is designed to provide tip clearance along the hull of the ship vessel. [1] The optimum diameter can be obtained using a calculation via the Troost series [1] by using the following formula:

D = 15.24(Ps)0.2
(n)0.6
Where D is the diameter;
Ps is the shaft horsepower;
N is the number of revolutions.

2.1.2 Speed (rpm):

The speed of the shaft is directly related to efficiency. At a low shaft speed, there is a high shaft torque produced. The speed rpm must differ from the resonant frequencies of other propulsion machineries.

A low rpm can increase propulsion efficiency by 10-15%.

2.1.3 Torque:

The amount of rotary force used to turn the shaft connected between the engine and the propeller is called Torque.

When power is given in HP then torque can be found as:

T = 5252.0 * HP / RPM [ft*lb] = 7121 * HP / RPM [Nm] [2]

2.1.4 Blade Surface Area:

Smaller the surface area of the propeller blade, larger is the efficiency as it provides a cutting effect through the water due to its streamlined nature. However, blades having a smaller surface area are more susceptible to cavitation as the thrust delivered by the propeller is subjected to the small surface area of the blades. Blade thickness on the other hand does not have much of an impact on the efficiency of the propeller but thicker blades induce larger suction and are hence more prone to cavitation.

2.1.5 Blade outline:

The most optimum blade curvature design would be broad at the roots, where they are connected to the hub via fillets and narrow or streamlined at the tips. Two important attributes of blade design are: rake and skew.

2.1.5.1 Rake:

The angle of a propeller blade relative to its hub is called rake. It is either flat (straight) or curved (progressive). It has no direct effect on the efficiency but the interaction between hull and propeller is significant. A larger rake requires a propeller to be of heavier make and overall increases the production cost.

2.1.5.2 Skew:

It is the tangential component of the angle formed between the radial line going through mid-chord point and radial line going through mid-chord section of the blade.

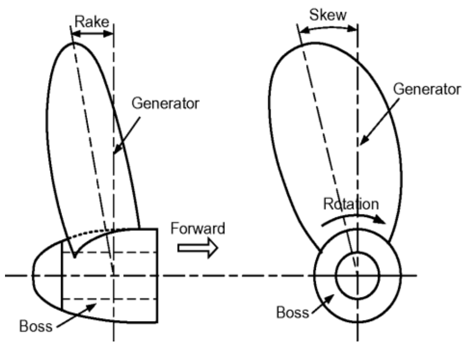

Fig 1: Diagrammatic representation of (a) Rake and (b) Skew [2]

2.1.6 Pitch/Diameter Ratio:

Pitch is nothing but the unit distance moved by a fixed solitary point and translated along the section nose tail line when one revolution is completed. It measures how much the propeller would drive or push forward. This ratio typically falls between 0.5 and 2.5 with an optimal value for most ship vessels being closer to 0.8 to 1.8. [2]

Studies and observations conclude that larger diameter increases efficiency but also increases drag force hence countering the acquired efficiency. Hence, an optimum pitch/diameter ratio is required for efficient propulsion.

2.1.7 Angle of Attack:

The angle of attack depends on the design lift of the blade. Larger the angle of attack, lesser would be the susceptibility to pressure side cavitation. It would thus be more susceptible to the suction side cavitation. Adjacently, if the angle of attack is reduced, the designed section would be more susceptible to pressure side cavitation than suction side cavitation.

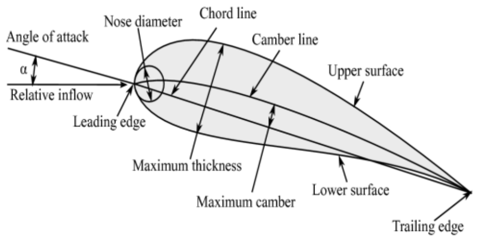

Fig 2: Diagrammatic representation of angle of attack and camber of blade [3]

2.1.8 Camber:

Camber refers to the curvature of the entire pressure face. Positive camber facilitates an increase in pitch from the leading edge to the trailing edge of the blade. The distance between the nose- tail line and mean line perpendicular to the former is called camber height. More the camber, larger is the impact on efficiency.

2.2 Miscellaneous Parameters of design influencing efficiency:

Apart from establishing values for the geometric entities that form the building blocks of the propeller design, there are some arbitrary concepts that need to factored into the design. These parameters are based on experimental research and observational analysis of the propeller in function.
2.2.1 Number of blades attached to the propeller hub:

Usually in the design of marine propulsion systems, the number of propeller blades range from 3-5. The 3 blade propellers are said to have maximum efficiency while the 4 blade propellers are used most commonly. The 3 bladed propellers have the least vibration. The 4 or 5 bladed propellers are used to increase surface area without increasing pitch diameter but they can also add to the turbulence in the water.

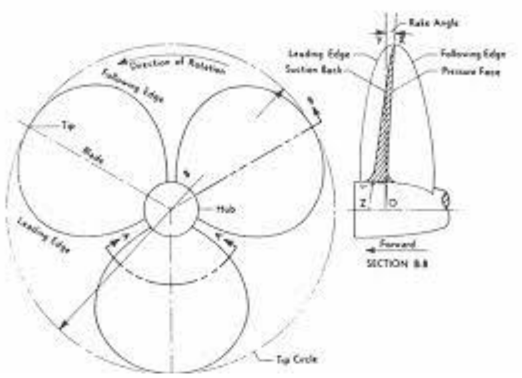

Fig 3: 3 bladed propeller diagrammatic representation for maximum efficiency [4]

2.2.2 Right handed-ness and Left handed-ness of propeller blade:

This “handed-ness” dictates the shape of the propeller. A right handed propeller always rotates clockwise while a left handed propeller always rotates counter clockwise. They can never be interchanged.

2.2.3 Interaction with hull:

Ship propellers perform in the wake region of the ship. This wake is defined as :

$w = 1- V_a / V_s$ [2]

If the propeller is attached close to the hull it can induce a low pressure on the hull and thus increase the drag force that it is subjected to. This will negatively impact the efficiency of the propulsion system. The propeller must produce enough thrust to overcome this drag hence it is crucial that it be attached at an adequate distance from the hull.

2.2.4 Fillet point fixture:

The blades of a propeller are radially attached to the hub by providing fillets at their ends to ensure a smooth and steady transition of the blade to the hub. The main function of this fillet is to provide a curvature in place of sharp cut edges so that these edges don’t break off due to shear forces. Due to their curved and smooth surfaces, the risk of the forces snapping of the blade from the hub is significantly minimized.

2.2.5 Counter force attachments:

To counter effects like frictional drag, cavitation, unnecessary vibrations and formation of keel vortices, certain accessories or devices need to be installed in the design.

2.2.5.1 Stern Tunnels:

Certain ships have V-shaped sterns which can have unnecessary vibrational effects. These effects are minimized by the use of Stern tunnels which reduce the wake peak effect. They are installed in a horizontal fashion above the propellers.

2.2.5.2 Schneekluth Ducts:

An optimum efficiency improviser, these devices redirect the flow of the water to the top part of the propeller to equalize the wake and hence reduce vibration. They can also be used to accelerate the flow through the propeller blades.

2.2.5.3 Grouches Spoilers:

Designed to prevent the formation of Keel vortices, these triangular shaped small plates are welded in the front, top and side portion of the propeller. They are used to redirect the flow horizontally through the blades.

2.2.5.4 Rudder Bulb Systems:

This is an energy saving device which is designed to improve propeller wake field. It also reduces the cavitation effect, thus vastly improving efficiency. It can even achieve a reduction in fuel emissions.

III. MATERIALS USED IN THE MAKING OF PROPELLERS

The types of materials influence the design process and the manufacture process greatly. The material needs to be corrosion resistant, light enough for effective propulsion, possessing great mechanical strength and most importantly, be economically viable for mass production.

Popularly, stainless steels and their alloys are used in their manufacture due to their high corrosion resistance and great mechanical properties However, there are some manufacturing processes like CNC manufacturing which use titanium and titanium alloys.

IV. MANUFACTURING METHODS OF MARINE PROPELLERS

As innovative and thoughtfully engineered the design of the propeller is, it all ultimately boils down to the finish obtained during the manufacturing methods. There are parameters like surface roughness and blade curvature that can we properly calculated using mathematical formulae but cannot always be achieved as desired in the manufacture. Hence, the method of manufacturing has a large impact on the efficiency of the propeller too.

4.1 Sand Casting method:

Sand casting has been once of the most standard manufacturing methods for the mass production of propellers. This traditional method is not complex and hence doesn't require skilled labor. The equipment required too isn't much and along with being feasible, it is also very economically viable. The process consists of 4 steps:

1. Layout
2. Pattern
3. Shaping
4. Finishing

4.1.1 Layout:

The very first step of sand casting includes a plan laid out showing the cross section of the blades, the blade outline, blade thickness, pitch diameter, rake angle and shrinkage of metal provision provided during the casting process. The layout is generally made of wood and this wood has to have a neat finish along with being clear of knots. [5]

The common number of layers used to build the layout on which the casting will occur are 19.

After this, a separate layout is made for determining the shapes of the original casts. [5]

4.1.2 Pattern:

Arranged in a cascading fashion, these wood layers are then ready for proceeding to the next step. These layers are planed down and smoothened. They are then arranged around a central drilled point which would represent the hub. Using an offset, the layers are glued together and then screws hold them in place. This is done till the layers start representing a propeller blade. [5]

4.1.3 Shaping:

Using specific tools, the pattern is then evened out and shaped well. Once the blade is finished, the hub is built. This hub uses cutoff pieces of the blade layers and there are shaped and fixed according to differing hub specifications. After this, the fillet radius is provided at the point where the blade meets the hub.

4.1.4 Finishing:

The small holes and dents in the wood are filled with wood fillers. The finishing of the propeller pattern is done using 80 grit sand papers [5]. Spray paint is used to fill scratches left behind by the sand papers. Further, the propeller is polished, smoothened and finished to perfection by using various paints and chemical solvents.

This was the case for wooden propellers. In case of marine propellers, the similar steps of layout, pattern, shaping and finishing are followed where in place of wood, the molten metal is poured into a sand cast of the pattern mold and then finished by using the machining functions in a lathe or industrial mechanism.

Fig 4: Casting process of a giant propeller (https://youtu.be/Di6fu7F2BxQ)

4.2 CNC Machining of propellers:

CNC machining is a rapid machining process for various metals. In the manufacture of propellers, the commonly used software in CNC manufacturing is MASTERCAM MILL X6. The advantages of CNC machining is that it can create intricate internal features, contrary to other manufacturing processes. [6]

Another software that can be used for the same purpose is HYPERMILL.

There are 5 distinct operations that are involved in this process:

1. Top Roughing
2. Top Finishing
3. Bottom Roughing
4. Bottom Finishing
5. Parting of Blade

This is however, a complex method of manufacture that requires a lot of skill, precision and accuracy. Along with a skilled user who should have adequate knowledge on how to operate the software, it is a time consuming and uneconomical process. It definitely favors our objective of maximizing efficiency but it cannot be implemented on a large scale.

4.3 Laser Engineered Net Shaping (LENS):

Especially used in making propellers out of titanium, this new and upcoming technology uses a high powered laser beam (1400W) to melt metal powder supplied to it coaxially [4]. Its advantage over other processes is , that it can create dense metal parts from propulsion with good metallurgical and mechanical properties.

However, the part requires post processing and needs to be cut from a substrate thus wasting a lot of material.

On viewing it from an efficiency point of view, due to its accuracy and good metallurgical properties it can definitely magnify the efficiency, but due to rough surface finish and additional post processing it cannot produce the most efficient design.

Overall, it is a great method of manufacture but it is not economical and it is still a process that is being explored.

4.4 Stereo Lithography:

An additive manufacturing process that utilizes an Ultraviolet beam to melt a photopolymer raisin which is then photochemically solidified into a single 3D layer of the propeller. It is another type of laser manufacturing technology.

It is a fast process that produces a protype strong enough to be machined and finished. Although it not used on a large scale, it can provide precision and hence enhance efficiency.

Even though it suits the objective, it is an inexpensive method that uses an expensive polymer raisin, hence defeating the purpose of economic manufacturing ultimately.

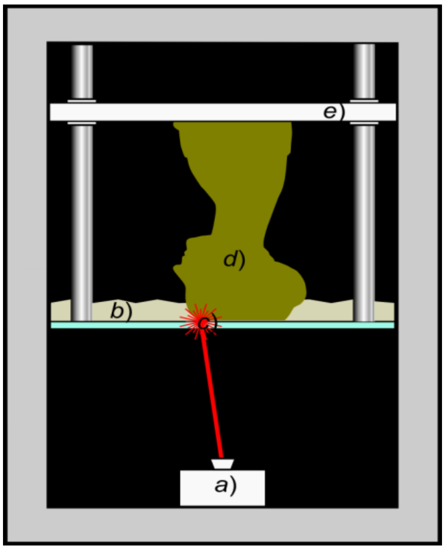

Fig 5: Stereo lithography process. [7]

4.5 Solid Ground Curing:

It is another photopolymer based additive manufacturing technique in which production of layer geometry is carried out using a UV lamp.

It can produce highly accurate products and does not need additional finishing. From an efficiency point of view, it can be a great manufacturing method but it is not economical and produces too much material waste.

V. CONCLUSION

On discussing the various design parameters and manufacturing methods to maximize efficiency, it is clear that from the geometric aspects to the miscellaneous factors, every miniscule point can have a large impact on the efficiency of the propeller and hence effect the ship propulsion. This paper can be considered as a thoroughly revised checklist that should be kept in mind while producing marine propellers for smooth and cost effective ship propulsion systems.

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