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LIGHT AIRCRAFT PROPELLER

[1] Mr. S. Sai Ram Reddy, [2] A.Mallikarjun, [3] S.Joshua, [4] MD. Subahan, [5] G.Navadeep
[1]Assistant Professor, [2345]Students
Department of Mechanical Engineering
Siddhartha Institute of Technology & Sciences, Narapally
sairamshery.mech@siddhartha.co.in, 25tq5a0316@siddhartha.co.in, 25tq5a0309@siddhartha.co.in, 25tq5a0308@siddhartha.co.in, 24tq1a0313@siddhartha.co.in

ABSTRACT

This work presents the design and computer-aided analysis of a two-blade, fixed-pitch propeller for a light aircraft powered by a four-cylinder engine of about 75 kW that turns the propeller directly at 2500 rpm. The propeller has a diameter of 1.75 m and a geometric pitch of 1.40 m at three-quarter radius, and it is intended for a two-seat training aircraft that cruises at about 180 km/h. The aim of the study is to arrive at a blade shape and a blade material that give good cruise efficiency, adequate static thrust for take-off, and a safe structural margin under the loads that act on a rotating blade.

The blade geometry was obtained with blade-element momentum theory. The blade was divided into twenty radial stations, and at each station the chord and twist angle were chosen so that the Clark-Y section works close to its best lift-to-drag ratio at the cruise advance ratio of 0.686. The resulting blade has a maximum chord of 135 mm at 35 percent radius, a tip chord of 70 mm, and a twist that falls from 42 degrees near the root to 15.5 degrees at the tip. The geometry was modelled in SolidWorks as a lofted solid through the twenty sections and exported to the analysis tools.

Aerodynamic performance was predicted in ANSYS Fluent using a rotating reference frame on a 180 degree periodic sector with about 4.2 million polyhedral cells and the k-omega SST turbulence model. At the design point of 50 m/s and 2500 rpm the computed thrust is 968 N, the shaft torque is 229 N m, and the propulsive efficiency is 0.807. The peak efficiency of 0.83 occurs at an advance ratio of 0.75, and the static thrust at zero forward speed is 1980 N. The blade-element estimate of cruise thrust was 1012 N, which lies within 4.5 percent of the CFD result.

The pressure field from the CFD solution was mapped onto the blade surface in ANSYS Mechanical and combined with the centrifugal load at 261.8 rad/s for static structural and pre-stressed modal analysis. Three blade materials were compared: a birch wood laminate, aluminium alloy 2024-T3, and a carbon/epoxy composite. The composite blade has the lowest propeller mass of 4.1 kg, a peak von Mises stress of 61.5 MPa, a tip deflection of 2.7 mm, and a first flapwise frequency of 148 Hz. The aluminium blade weighs 10.9 kg for the propeller, and the wood blade has a first mode only 15 percent above the 2P excitation.

I. INTRODUCTION

The propeller is the component that turns engine power into thrust in most light aircraft, microlights and trainers. Its blades act as small rotating wings, and the angle at which the air meets each section changes with radius, forward speed and rotational speed. A fixed-pitch propeller can only be at its best for one combination of these, so

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the designer has to decide whether the blade should favour take-off and climb or cruise. Even a few percent of efficiency affects fuel use, range and climb rate, and a poorly matched propeller can also prevent the engine from reaching its rated speed.

Propeller blades also carry some of the most severe loads found on a light aircraft. At 2500 rpm the tip of a 1.75 m propeller moves at about 229 m/s, and the centrifugal force on each blade is many times the blade weight. Aerodynamic thrust and torque bend the blade forward and in the direction of rotation, and the engine firing pulses excite the blade at fixed multiples of the rotational speed. A blade that is strong enough in static terms can still fail in fatigue if one of its natural frequencies lies near these excitation frequencies.

Small propeller makers have traditionally relied on empirical charts, earlier blade shapes that are known to work, and repeated ground runs on a test stand to settle a design. This approach is slow and it gives little insight into why a blade behaves as it does.

The present work applies such a workflow to a two-blade fixed-pitch propeller for a light two-seat aircraft. Blade-element momentum theory is used to define the chord and twist, SolidWorks is used to build the blade model, ANSYS Fluent is used to compute thrust, torque and efficiency over a range of advance ratios, and ANSYS Mechanical is used for static structural and modal analysis under combined centrifugal and aerodynamic loading.

II. LITERATURE SURVEY

The theory of propeller aerodynamics developed from two separate ideas that were later joined. Momentum theory treats the propeller as an actuator disc that adds momentum to the stream of air passing through it, and it gives an upper limit to the efficiency that any propeller can reach for a given thrust loading. Blade-element theory, on the other hand, divides each blade into narrow strips and calculates the lift and drag of every strip from two-dimensional airfoil data. Combining the two produces blade-element momentum theory, in which the induced velocity at each radius is found from a balance between the blade forces and the momentum change of the annulus of air passing that radius. Many textbooks and design studies describe this method as accurate enough for preliminary design of light aircraft propellers, provided that tip-loss corrections are included and that reliable section data are available at the correct Reynolds number.

Studies on optimum propeller shape have shown that minimum induced loss is obtained when the trailing vortex sheet moves backward as a rigid helical surface. Design procedures based on this condition give the chord and twist distribution that achieves a required thrust or absorbs a given power with the least loss, and they are widely used to lay out new blades. Work on section choice has compared the Clark-Y, the RAF series and the NACA four-digit and sixteen-series sections for light propellers. The Clark-Y section has remained popular for small fixed-pitch blades because its flat lower surface simplifies manufacture and its behaviour at moderate Reynolds numbers is well documented. Research has also noted that thick sections are

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needed near the root for strength, which forces the inner part of the blade to work at lower lift-to-drag ratio than the outer part.

Computational fluid dynamics has been applied to propellers in increasing detail over the last two decades. Early work used panel methods and vortex-lattice models, while more recent studies solve the Reynolds-averaged Navier-Stokes equations around the full blade. The rotating reference frame, also called the multiple reference frame approach, is commonly used for steady propeller analysis because it allows the flow around a rotating blade to be solved as a steady problem. Periodic boundaries are used to model only one blade passage, which reduces cell count considerably. Studies comparing these predictions with wind-tunnel measurements on small propellers report agreement in thrust and power coefficient within a few percent over the main operating range, with larger differences near zero advance ratio where the flow over the inner blade separates. The k-omega SST turbulence model is generally reported to give better separation behaviour than the standard k-epsilon model for such flows.

Structural work on propeller blades has concentrated on centrifugal tension, bending from thrust and torque, and vibration. Investigations of wooden propellers have described the importance of laminate direction, moisture content and root design, and have reported that most wooden blade failures begin at the hub bolts or at the root fillet. Studies on aluminium alloy blades have emphasised fatigue, since surface damage from stones and corrosion can start cracks that grow under the cyclic loads of engine firing. Finite element analysis is now used routinely to find the stress distribution in a blade and to compute its natural frequencies with centrifugal stiffening included. Research on resonance has shown that the first flapwise mode should be kept clear of the 1P and 2P excitations, and a margin of about 15 percent or more is commonly recommended in design practice for direct-drive engines.

Composite materials have been studied as an alternative to wood and aluminium for small propellers. Carbon/epoxy blades made with a foam core and unidirectional spar layers are reported to be much lighter and stiffer than equivalent wooden blades, with good fatigue resistance and little sensitivity to moisture. Studies have also shown that a lighter blade reduces the gyroscopic loads on the engine mount and the polar moment of inertia of the drive train, which affects crankshaft vibration. The literature therefore suggests that material selection for a light aircraft propeller should consider mass, stress margin, stiffness, frequency placement, cost and repairability together, which is the approach followed in the present study using a coupled blade-element, CFD and finite element workflow.

III. SYSTEM ANALYSIS

The problem addressed in this study is the design of a two-blade fixed-pitch propeller of 1.75 m diameter for a light aircraft whose engine delivers about 75 kW at take-off and 60 kW at cruise, with the propeller turning directly at 2500 rpm. The propeller must give a cruise efficiency above 0.80 at 50 m/s, which corresponds to an advance ratio of 0.686, and it must provide enough static thrust for a short take-off run without overspeeding the engine. The tip speed of 229 m/s must stay well below the speed of sound to avoid compressibility losses and noise. Structurally, each blade must withstand the centrifugal force at 261.8 rad/s together with thrust and torque bending,

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with a factor of safety of at least 2.5 on material strength, and its first flapwise natural frequency must be at least 15 percent away from the 1P frequency of 41.7 Hz and the 2P frequency of 83.3 Hz. The blade mass should be as low as possible to limit gyroscopic and inertia loads on the engine.

Existing System

In conventional practice a fixed-pitch propeller for a light aircraft is often sized from empirical charts that relate engine power, rotational speed and flight speed to diameter and pitch, or it is copied from an earlier blade that is known to suit a similar engine. The pitch is then adjusted by experience, and the final blade is carved from a wood laminate or machined from an aluminium forging. Its performance is checked by static thrust runs on an engine test stand and by flight trials, and in some cases a scaled model is tested in a wind tunnel. Each change in pitch or chord means a new blade and a new round of tests, so only a few variants can be tried in practice. Stresses are estimated with simple beam formulas at the root, and vibration problems are usually found only after cracking is seen in service. The approach gives little information on how load is shared along the blade, and comparing different materials on equal terms is difficult and expensive.

Disadvantages of Existing System

- Diameter and pitch are taken from empirical charts that only approximate the actual aircraft and engine.
- Every change in blade shape requires a new prototype to be carved or machined.
- Static thrust stand runs do not show the cruise efficiency at the design advance ratio.
- Wind-tunnel testing of scaled propellers is costly and suffers from Reynolds number mismatch.
- The distribution of thrust and torque along the blade radius is not known.
- Root stresses are estimated with simple beam formulas that ignore twist and section shape.
- Natural frequencies are not checked, so resonance with engine firing may be found only in service.
- Different blade materials cannot be compared on the same geometry without making several blades.
- Flow separation near the root at low speed cannot be seen or corrected.
- Design knowledge stays with individual craftsmen and is hard to document or repeat.

Proposed System

The proposed approach replaces most of the trial-and-error steps with a computer-aided design and simulation workflow built around blade-element momentum theory. The design point of 60 kW, 2500 rpm and 50 m/s is entered into a blade-element program that divides the blade into twenty radial stations and selects chord and twist so that each Clark-Y section works near its best lift-to-drag ratio, with Prandtl tip-loss correction. The chord and twist table is used to build a lofted blade in SolidWorks,

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with a 150 mm hub radius and a thickened root that blends into the hub. The blade is analysed in ANSYS Fluent with a rotating reference frame on a periodic sector to compute thrust, torque and efficiency over advance ratios from 0 to 0.9. The surface pressures at the design point and at static thrust are transferred to ANSYS Mechanical, where static structural and pre-stressed modal analyses are carried out for birch laminate, aluminium 2024-T3 and carbon/epoxy. If any limit on efficiency, stress or frequency is not met, the twist or chord is revised and the loop is repeated.

Advantages of Proposed System

- Chord and twist are derived from blade-element momentum theory for the actual design point.
- Thrust, torque and efficiency are predicted for the full range of advance ratios before manufacture.
- The CFD solution shows local flow separation and pressure distribution on every part of the blade.
- Several blade shapes can be compared in a day without carving or machining any prototype.
- Centrifugal and aerodynamic loads are applied together in a single structural analysis.
- Pre-stressed modal analysis gives natural frequencies that include centrifugal stiffening.
- Wood, aluminium and composite blades are compared on exactly the same geometry and loads.
- Stress concentrations at the root fillet and hub are located before any testing.
- The parametric CAD model allows quick changes when the engine or aircraft changes.
- Only the final blade needs a ground-run test, which saves time and material.

IV. METHODOLOGY

The methodology starts with the design requirements: shaft power of 60 kW at cruise, propeller speed of 2500 rpm, flight speed of 50 m/s, and a diameter limit of 1.75 m set by ground clearance. Clark-Y section data for lift and drag at Reynolds numbers between 0.5 and 1.5 million are prepared, and the blade-element momentum program iterates the axial and tangential induction factors at twenty stations to obtain the chord and twist that give a cruise thrust of about 1000 N. The resulting table is imported into SolidWorks, the sections are lofted into a solid blade and patterned to form the two-blade propeller with its hub. In ANSYS Fluent a 180 degree periodic sector with a rotating reference frame is meshed with 4.2 million polyhedral cells and prism layers that give y plus near one, and the k-omega SST model is solved at advance ratios from 0 to 0.9. Thrust, torque and efficiency are recorded. The pressure load is mapped to ANSYS Mechanical, centrifugal load is added, and stress, deflection and pre-stressed modes are found for each material before results are compared.

SYSTEM ARCHITECTURE

The design workflow is arranged as a closed loop around the blade-element design stage. The Requirements block holds the engine power, rotational speed, flight speed

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and diameter limit, and the Airfoil Data block supplies Clark-Y lift and drag coefficients. Both feed the Blade-Element Momentum Design stage, which outputs the chord and twist distribution at twenty stations. The CAD Modelling stage in SolidWorks turns this table into a lofted blade and hub assembly. From the CAD model the work divides into an aerodynamic branch and a structural branch. In the aerodynamic branch, ANSYS Fluent with a rotating reference frame and k-omega SST produces thrust, torque, efficiency and the surface pressure field. In the structural branch, ANSYS Mechanical applies the mapped pressure and the centrifugal load to give stress and deflection, and a pre-stressed modal analysis gives natural frequencies, repeated for birch laminate, aluminium 2024-T3 and carbon/epoxy. The Design Evaluation block checks efficiency, factor of safety and frequency margin, and either sends revisions back to the blade-element stage or releases the final blade and material choice.

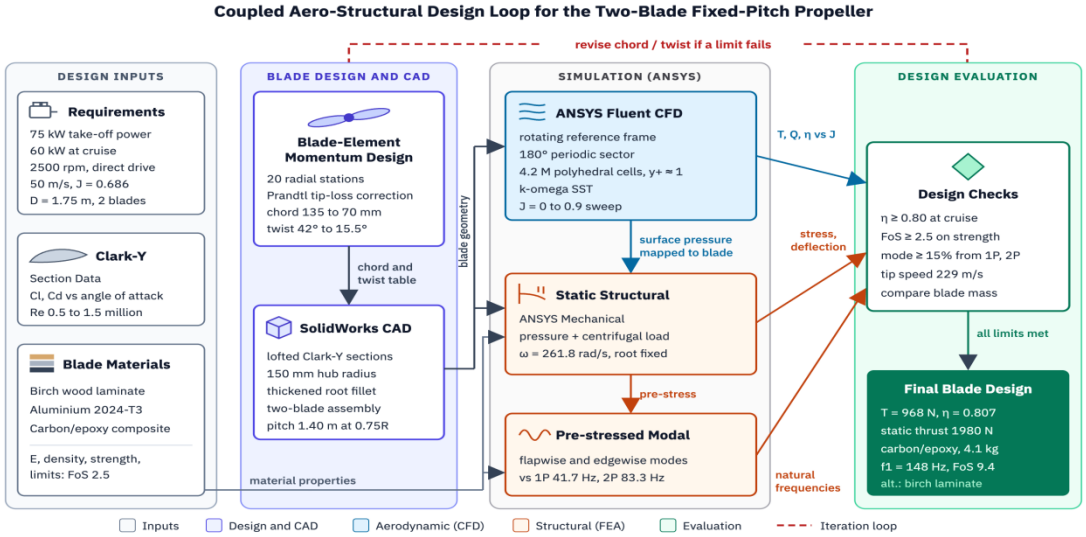


Fig. 1 System Architecture

V. RESULT AND OUTPUT

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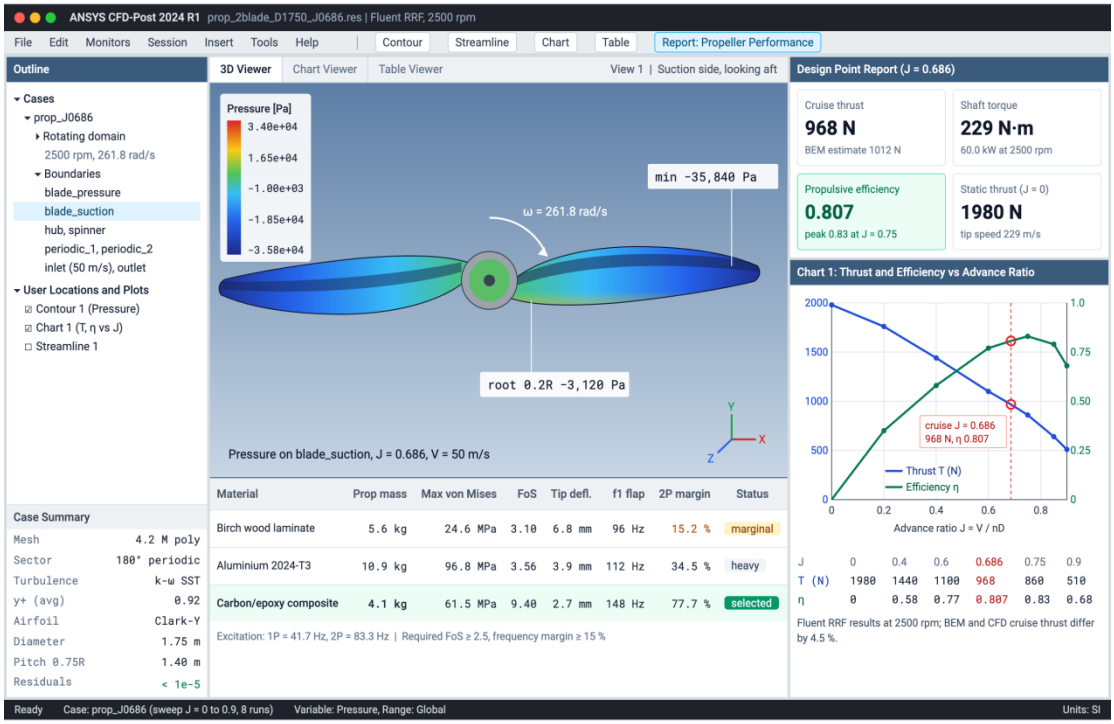


Fig. 2 Result and Output Screen

VI. CONCLUSION

A two-blade fixed-pitch propeller of 1.75 m diameter for a light aircraft has been designed and analysed using blade-element momentum theory, SolidWorks modelling, ANSYS Fluent CFD and ANSYS Mechanical structural and modal analysis. The blade-element stage produced a Clark-Y blade with a maximum chord of 135 mm and a twist from 42 to 15.5 degrees, and the CAD model reproduced this geometry accurately for the later stages of the work.

The CFD results show a cruise thrust of 968 N and a propulsive efficiency of 0.807 at 50 m/s and 2500 rpm, with a peak efficiency of 0.83 at an advance ratio of 0.75 and a static thrust of 1980 N. The difference of about 4.5 percent between the blade-element and CFD thrust confirms that the simpler method is suitable for laying out the blade, while CFD is needed to see root separation and the exact pressure field used for structural loading.

Among the three materials, the carbon/epoxy blade gave the lowest propeller mass of 4.1 kg, the lowest tip deflection of 2.7 mm, a factor of safety of 9.4 and the highest first flapwise frequency of 148 Hz, well clear of the 2P excitation at 83.3 Hz. The aluminium 2024-T3 blade was safe with a factor of safety of 3.56 but more than twice as heavy, and the birch laminate blade, though light and cheap, had a frequency margin of only about 15 percent. The carbon/epoxy blade is therefore recommended, with the wood laminate as a lower-cost alternative.

Future work will include making a prototype blade and measuring static thrust and torque on an engine test stand to validate the predictions, a transient sliding-mesh

study of the interaction between the propeller slipstream and the engine cowling, prediction of tip noise, and a fatigue assessment of the composite root and hub joint under repeated engine firing loads.

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