Abstract

An experimental study of propeller efficiency was conducted with two axial-symmetric models of different diameters, and also for tractor/pusher propeller configurations. The experiments were conducted under static conditions and two different flows speeds inside the high-contraction wind tunnel located at Purdue Aerospace Sciences Laboratory (ASL). The thrust generated by the propeller and the supplied power were measured. The propeller efficiency was compared at various test conditions and propeller configurations. It was found that the smaller body produced more thrust and higher propeller efficiency than the bigger size body. It was also determined that the pusher propeller configuration was more efficient than the tractor.
1. Introduction

The recent advances in propeller technology have led to an increased interest in understanding the effects of the slipstream on nearby aircraft components. Since the motor-driven propeller actively affects the propulsion, aerodynamics and stability of the aircraft, the need to optimize its integration with supporting structures such as wings and fuselages is paramount. Consequently, the study of the effects of various propeller configurations and fuselage sizes on drag and lift performance are of great importance.

It has become imperative to understand the interaction of a propeller configuration with the supporting structures such as fuselage and wings in order to determine optimal system integration. For this reason, experimental as well as numerical studies of propeller-body interaction have been undertaken in previous research work placing emphasis on understanding effects on the body rather than looking at the system as a whole.

This study aims to experimentally and analytically investigate the combined performance of propeller-fuselage to understand the complex flow behavior of the slipstream at various propeller configurations. Qualitative and quantitative experimental results will provide insights into understanding the effects of fuselage size and propeller position on the overall system.
2. Background

A propeller is a device that converts power to thrust force to propel a vehicle such as an airplane, ship, or submarine through a fluid by rotating a number of twisted blades about a central axis. The Wright brothers were the innovators of the propeller propulsion system. The propulsion system used by them was a set of twin pusher propellers behind the wings driven by a small motor. Since then, scientific advances in the design and performance of propellers have considerably increased. Due to high demand for improvement of propeller propulsion for small aircraft in the recent years, propeller research has expanded to enhance the understanding of propeller interaction with other aircraft components as well as to improve propeller design and efficiency.

The cross-sectional shape of the propeller blades is similar to that of an airfoil. The mechanism by which the propeller operates consists of creating pressure differences across the blades because of their spinning motion. The spinning motion of the propeller causes air to accelerate past it creating a thrust force that moves the aircraft forward. The blade tips of the propeller move faster than the center hub. The twist of the blades allows higher propeller efficiency by allowing the blade to operate at an optimal angle of attack.

There are two main propeller-fuselage configurations: tractor and pusher. The pusher configuration places the propeller behind the engine that drives it. The thrust produced pushes the airplane forward. The tractor propellers are placed at the front of fuselage that holds it. In this way, the thrust produced by the propeller pulls the aircraft forward.

One of the main advantages of the pusher configuration is the reduced fuselage drag because of the favorable pressure gradient produced by the propeller in the stream-wise direction. Also, the pusher configuration offers better visibility to the pilot compared to the tractor configuration. However the location of the engine-propeller in a pusher arrangement at the rear of the fuselage results in a significant reduction in propeller efficiency. An experimental investigation found in the literature showed that the efficiency of a propeller
mounted behind a fuselage was reduced to 75 percent, compared with an uninstalled propeller of 85 percent [18]. This is due to the turbulent and lower momentum air captured by the propeller after the air has passed the fuselage body, not only reducing efficiency, but also causing vibration, stresses, and noise in the propeller.

The tractor configuration has several advantages over the pusher configuration. Because of the location of the propeller at the front of the fuselage, the propeller gets clean air from the main stream airflow. The turbulence captured by the propeller is much lower than in the case of the pusher configuration because of its location with respect to the fuselage, thus the tractor configuration provides higher propeller efficiency. The location of this configuration also produces a more reasonable center of gravity for conventional aircraft. Some of the disadvantages are higher fuselage drag due to the prop-wash effect and reduced visibility for the pilot. There are also slipstream-tail/wing interactions that could create control problems.

Theoretically, drag is described by Equation 1.

\[
D = \frac{1}{2} \rho V^2 C_d L \tag{Equation 1}
\]

It is common practice to express propeller performance work in terms of advance ratio and efficiency. The advance ratio \(J\) is a measure of the local flow angle at the blade tip [12]. Equation 2 shows the mathematical representation of the non-dimensional advance ratio.

\[
J = \frac{V_0}{nd} \tag{Equation 2}
\]

The propeller efficiency is defined as shown in Equation 3.

\[
\eta = \frac{T V_0}{P} \tag{Equation 3}
\]

Where \(V_0\) is the free stream velocity, \(d\) is the propeller diameter, \(n\) is the rotation speed (Hz), \(T\) is the measured thrust (N), and \(P\) is supplied shaft power (W).
3. Apparatus

In order to measure drag and lift on two different size bodies at different free stream conditions, it was necessary to utilize the Purdue high-contraction wind tunnel. The bodies and the motor-propeller system had to be designed and assembled. The following is a description of the wind tunnel used as well as the design and construction procedure of the two test bodies.

3.1. High Contraction Wind Tunnel

The high contraction wind tunnel has an 18 inch diameter test section with a two component balance for lift and drag. The circular test section was originally designed to test propellers. The maximum free stream velocity produced by the wind tunnel is 120 ft/sec. Figure 1 shows a picture of the high contraction wind tunnel used in the present experimental investigation.

![Figure 1 - High Contraction Wind Tunnel](image)
3.2. Fuselage Model

In order to contrast the effects of fuselage size and propeller configuration on drag and efficiency, it was necessary to design and manufacture propeller-body models for testing in the high contraction wind-tunnel. A fuselage shape was selected from the NACA 6-digit series airfoils. The model curves 63-020A and 63-035A were selected for the design of the small and large fuselage bodies, respectively. The curves were imported to the CAD program CATIA which yielded, as a result, an axial-symmetric shape that was formed using a volume of revolution command, as shown in Figure 2.

![Figure 2 – Illustration of two models](image)

The models were cut in halves and each of the models was carefully designed in their interior to accommodate the motor and other components for pusher and tractor configurations. Careful interior design and manufacture of spaces to fit the motor, shaft, and mounting plate were completed, as shown in Figure 3.
Figure 3 – Interior of the models

Figure 4 and Figure 5 show drawings specifying the selected dimensions for the small and big size fuselage models, respectively.

Figure 4 – Small fuselage model (dimensions in \textit{mm})
Additionally, a mounting plate was designed to mount the models on the balance in the high contraction wind tunnel. The plate has a slit in the middle to fit power electric wires and two screw holes to mount the model on the balance.

Both models were machined with a 5-axes CNC milling machine at the ASL. The material was 3/4 inches MDF plates stacked and glued.
A careful selection of propeller dimensions and motor requirements was undertaken for appropriate thrust generation. A 2-bladed, 8 inch diameter, 6 inch pitch plastic propeller was selected and a generic 12-24V DC brushed motor was used. A 1/8 inch shaft was coupled with the motor using a machined coupler. A proper ball bearing was selected and the inner ring of the bearing was fixed to the shaft. The motor-propeller assembly was assembled to the constructed model, and by running the motor, it was checked whether the vibrations were within an acceptable range. Optimal balancing was accomplished by
tweaking the coupling angle between the shaft and the propeller mounting plane to reduce vibration. Figure 8 shows a picture of the motor, shaft, ball bearing, and coupler assembly used.

![Figure 8 – Motor, coupler, shaft, and ball bearing](image)

Mounting plates were machined at the ASL shop and glued to the model. Figure 9 shows the inside of the small model with the motor and mounting plates attached to the model.

![Figure 9 – Mounting plate, motor-shaft assembly and wires](image)

An adjustable DC power supply, two multi-meters, a thermometer, and a laser RPM counter were the equipment used to make measurements. The test model was mounted on
the balance in the high-contraction wind tunnel using two screws to fix the model to the support, as shown in the Figure 10.

![Figure 10 – Small model with propeller in the wind tunnel](image)

For various tests using tractor and pusher configurations with both fuselage sizes in the high contraction wind tunnel, the set-up of the apparatus was carefully done so that each condition would be accurately modeled.

### 3.3. Equipments Listing

- Two fuselage models
- 12V brushed DC motor
- 8 inches X 6 inches propeller
- Shaft, ball bearing, and coupler
- Adjustable DC power supply
- Two multimeters for voltage and current measurements
- Optical RPM counter
- Thermometers
- Watch
4. Procedure

4.1. Calibration of the Balance

The balance was calibrated by plotting the weights applied to the balance as a function of output voltage and curve-fitting the data with linear functions.

4.2. Drag Coefficient of the Bodies

The bodies without propeller were mounted and the wind tunnel was run in the range from zero to one inch of water dynamic head, with 0.1 inches of water increments. The drag was plotted as a function of velocity and curve-fitted to a quadratic function. The coefficient was used to obtain drag coefficients of each body.

4.3. Main Test

The propeller was mounted to the model and the motor was run up to 20W by increasing the voltage. Tests were repeated at two different wind-tunnel speeds of 0.1 and 0.4 inches of water (6.38 m/s and 12.75 m/s) and at no flow velocity (0 m/s). Drag was recorded by reading the output voltage of the balance. High contrasting black and yellow tape was attached around the propeller mounting part which aid to visualize the number of counts per revolution with the digital laser RPM. Propeller RPM was obtained by aiming the laser RPM counter to the color-alternating tape.
Input voltage and current were measured with multimeters. For some test runs, temperature and running time was also taken.

4.4. Flow Visualization

The models were painted in white to contrast the black paint/oil. A paint/oil mixture was applied in lines, spots, and dots to visualize the flow on the surface of the bodies. Tufts were also applied in three rows.
5. Results and Analysis

5.1. Balance Calibration

At first, the weights in ounce units were used to calibrate the wind tunnel. However, it was observed that some of these were not accurate because their caps were open. Then, it was decided to repeat the calibration using weights in metric units (grams). Voltage data for drag was recorded as the weights in the balance calibration of the wind tunnel were changed. A curve fit of each of the data sets was accomplished to obtain an equation to use in the calibration of the data. Figure 12 shows the balance calibration results using these two different sets of weights. The curve fits and final equations are also shown.

![Balance Calibration Graph](image)

As observed in Figure 12, the curve fit equations for the data obtained using two different sets of weights are very close. The R-squared values for each set of data are very close to 1, indicating that the result is highly linear. The last data set specified with the name Drag #4
was used to calibrate the data. Since the curve fit results were very close to each other, any of the curve fit equations could have worked to calibrate the data accurately.

5.2. Temperature Effects in Measurements

During the early stages of the experiment, it was found that the pusher configuration produced slightly more thrust than the tractor. It was thought that the tractor configuration measurements of thrust and power were dependent on temperature, since the opening from the model allowed air to cool the motor better than the tractor configuration. In order to investigate this argument, a specially designed set of measurements was undertaken. The voltage supplied to the propeller was kept constant and values of power, drag and temperature were recorded in one minute intervals for the tractor configuration. A digital thermometer was connected to the inside of the body to estimate the motor temperature. A more accurate measurement would have included a thermometer placed exactly inside the motor; however this was impossible in this experimentation. Figure 13 shows the change in thrust/power measurements with change in temperature.

![Figure 13 - Data measurement dependence on temperature results](image-url)
It is observed in Figure 13, that the change in thrust over power measurement is not significant as the temperature increases in the motor, inside the fuselage model. Hence, according to these results, temperature does not directly affect significant changes in data measured.

**5.3. Drag of Bodies without Propeller**

In order to resolve the contribution of the propeller to the propeller-body system, a baseline for the drag of the bodies needed to be experimentally determined. Figure 14 shows the drag of the bodies at different flow velocities. For reference, the propeller tests were ran at static 6.38 and 12.75 m/s.

![Drag vs. Velocity](image)

Since drag is generally proportional to velocity squared (Equation 1), by fitting a quadratic curve through the data points, the average drag coefficient can be easily calculated. The average $C_d$ of the large body is about 0.011 with respect to length, and the $C_d$ of the small body is about 0.0049, less than half that of the large body.
In inviscid flows, the $C_d$ of any object would be constant. However, in real world applications the viscosity effect in the boundary layer and the effect of changing transition locations cause $C_d$ to vary. Having tested the model at different velocities, the variation of $C_d$ with respect to Reynolds number can be studied. Figure 15 illustrates the effect of Reynolds number on the $C_d$ of the model. For most airfoils, increasing Reynolds number causes a reduction in coefficient of drag, due to more energetic boundary layers. This effect can be seen for both of the models, but it is more evident on the smaller model.

![Drag Coefficient Dependence on Reynolds Number](image)

**Figure 15 - The effect of Reynolds number on drag coefficient**

### 5.4. Thrust Comparison

Thrust was recorded by reading the drag output off the balance. By plotting all results in one graph, comparisons of thrust curves between body sizes, propeller configurations and different tunnel speeds are possible. The legend is organized to recognize model size, propeller configuration and tunnel speed. ‘S-’ and ‘L-’ stand for small and large models respectively, and the velocity in the brackets are tunnel speeds.
Figure 16 – Thrust vs. power input

Figure 16 shows that the pusher configuration generates more thrust in most cases. Differences of thrust between different propeller configurations are greater in the larger body when there is flow in the tunnel. The only case that the tractor configuration generates more thrust at static conditions is in the case of the larger body. At above 7W input power the tractor produced more thrust than the pusher. The result of this specific case seemed like an experimental error, but it is confirmed with repeated tests.

Thrust curve is shifted down almost parallel as tunnel speed goes up with slight slope decrease. The points on the zero thrust line show the equilibrium between the thrust produced by the propeller and the drag generated by the wind tunnel. For example, the large body in the tractor configuration requires 15 W of power input to the propeller to cancel the drag forces, whereas the pusher requires less than 10 W.
5.5. RPM Comparison

The RPM of the propeller was measured with an optical RPM counter and the results were plotted in Figure 17 for comparison.

When the tunnel was running, propeller delivered kinetic energy to the shaft, and the motor converted it into electrical energy. This effect is observed in the plot. As seen, the small body in the tractor configuration at 12.8 m/s of tunnel flow develops 3700 RPM when no power is supplied. Neither of the configurations affected significantly the RPM of the propeller at the same experiment conditions. Body sizes had negligible influence on RPM at 0 m/s and 6.38 m/s of tunnel speed. At 12.8 m/s however, the larger body had lower RPM with both tractor and pusher configuration than the smaller body.
5.6. Propeller Performance

The propeller efficiency versus the advance ratio for different propeller configurations and tunnel velocities is shown in Figure 18 and Figure 19.

According to the definition and equation of advance ratio shown in Equation 2, no useful thrust can be generated for advance ratios above 0.75, for the particular case of the dimensions of the propeller in this experimental investigation. This is due to the fact that the propeller blades would be operating in negative angles of attack above this advance ratio limit.

The thrust was obtained from the wind tunnel balance, and the power was calculated from the voltage and current supplied to the motor. For this analysis, the drag from the bodies without the propeller was subtracted from the motor thrust hence the performance of the propeller alone can be analyzed on its own.

Since the motor efficiency could not be isolated, this efficiency is actually the motor efficiency multiplied by the propeller efficiency. It is estimated that for a DC brushed motor similar to the one used, the motor efficiency is about 50-70%. This means that the magnitude of the efficiency curve is likely to be much lower than the actual propeller curve. However, since the goal of the experiment is to compare the difference between pusher and tractor configurations, the absolute value of propeller efficiency is not as important. Nevertheless, using the highest curve in Figure 18, which is the data for the small model in the pusher configuration at 6.38 m/s, a peak total efficiency of 47.5% can be observed. Estimating the motor efficiency to be 60%, the peak efficiency of the propeller can be estimated to be around 80%.
As Figure 18 shows, at the wind tunnel speed of 6.38 m/s the small body in pusher configuration is much more efficient than the rest of test combinations. For the small model, an efficiency increase of 3% to 15% was observed, whereas for the larger model the efficiency increase was as much as 20%.

As shown in figure 19, at 12.75 m/s, the difference in efficiency between tractor and pusher configurations for the larger model is more evident. At the advance ratio of 0.73, the improvement in efficiency for the tractor configuration is of about 50%.
It is interesting to note that the small model in the tractor configuration had higher efficiency for an advance ratio above 0.775. However, as mentioned before, the efficiency data above an advance ratio above 0.75 is not very meaningful, since the propeller is no longer producing any significant thrust. Due to limitations of the amount of voltage and current the motor can handle, advance ratios below 0.70 could not be tested. Without more data below an advance ratio of 0.70 the experiment at wind tunnel speed of 12.75 m/s for the small model is not very conclusive.

5.7. Flow Visualization

In order to enhance the understanding of slipstream flow behavior on the surface of the two body sizes, it is necessary not only to take quantitative data but also to observe the flow behavior qualitatively. Flow visualization methods provide the opportunity to observe the path followed by the slipstream on the surface of the body.
First, a mixture of oil and black paint was used to try to visualize the slipstream path past the leading area of the fuselage body. Patches of paint were positioned in the surface of the body. Figure 20 and Figure 21 show the 35% size body with oil/paint mixture in its surface and without the propeller installed at 6.38 m/s tunnel velocity.

As observed in both figures above, the oil/paint mixture is affected by the free stream but it is also greatly affected by gravity. The mixture fails to accurately show the path of the slipstream because gravity pulls the mixture downward. Hence, the oil/paint mixture painted in patches in the surface of the body did not accurately showed the flow behavior in the surface of either of the bodies.

The great concentration of oil/paint mixture in the patches painted along the surface of the body was thought to be responsible for the failure of the method. Then, dots of the same mixture were painted along the surface of the body. It was thought that the oil/paint dots in the surface of the body would more accurately reflect the behavior of the slipstream. After the tunnel was turned on, pictures were taken rapidly since the low concentration of oil/paint mixture would be more prone to motion from the free stream velocity. Figure 22 and Figure 23 show the results of this second flow visualization attempt.
As observed in the figures above, the oil/paint mixture was again greatly affected by gravity. An accurate visualization of the flow path in the surface of the body is not possible.

The third attempt to visualize the flow on the surface of the fuselage made use of small tufts taped to the surface of the body. The tufts were taped along the surface longitudinally with respect to the free stream flow. Figure 24 and Figure 25 show the flow visualization results for both fuselage sizes in the tractor configuration.

This flow visualization method was much more successful than the oil/paint method. From the pictures it is hard to visualize the slipstream behavior on the surface of the fuselage. However, from direct experimental observation, it was possible to see that the last row of tufts in the trailing side of the fuselage was experiencing different motion than the rest of the tufts on the surface. The two lines of tufts positioned right after the propeller showed no signs of non-uniform flow. These tufts followed the longitudinal direction of the free
stream flow. The last line of tufts showed the tufts separating from the surface of the body. Thus, this maybe evidence that flow separation occurred in the trailing side of the body.

Figure 26 shows the same arrangement of tufts but with the propeller positioned in the pusher configuration.

![Figure 26 - Tufts in 35% fuselage in pusher configuration](image)

In the pusher configuration, it was possible to see that the tufts showed disruption in the longitudinal flow motion in the same region as that of the tractor configuration. These observations were all purely qualitative since it is impossible to observe them from looking at the figures shown in this report.

6. Conclusion and Discussion

6.1. Major Conclusions

In this experiment, a study of propeller efficiency was conducted with two axial-symmetric models of different diameters, and also for tractor and pusher propeller configurations.

In order to eliminate sources of error, many balance calibration measurements were taken. It was shown that the balance was capable of producing reliable data. A temperature dependence test was conducted. It was found that temperature had no major impact in propeller-motor performance.
The drag of the axial-symmetric bodies was measured without the propeller. It was found that the larger body had roughly twice as much drag as the smaller body. The drag data was used in later experiments to normalize the propeller efficiency.

It was also found that the smaller body-propeller system produced higher thrust at a given power input in all cases compared to the larger body; and the pusher configuration generally produced more thrust than the tractor configurations.

The efficiency data suggests that for axial-symmetric bodies without any protruding wings or fins, the pusher configuration is generally more efficient. Comparing the difference between the small (20% thick) and large bodies (35% thick), it seemed that the benefit of the pusher configuration increases as the thickness of the airfoil increases.

6.2. Limitations

Since the balance could only be calibrated in the positive drag direction, it was assumed that the measurements could be extrapolated to the negative direction. Without any data in the negative direction, the accuracy of the balance cannot be confirmed.

Without knowing the efficiency of the motor, the exact efficiency of the propeller could not be calculated. This is acceptable for comparison studies, but if more detailed conclusions were to be drawn from this experiment, a motor of known power curve and efficiency data should be used. Or, if equipment is available, the motor used could be tested on a dynamometer to obtain its performance parameters.

Due to limitations of the amount of voltage and current the motor and power supply can handle, advance ratios below 0.70 for the 12.75 m/s conditions was not possible to test. A more powerful motor and power supply would be needed for high flow velocities. It is also possible to run the experiment at a lower velocity. For example at 8 m/s, the system would require much less power than at 12.75 m/s.
After an exhaustive search for existing literature comparable to the present experimental investigation, it is not possible to compare the present investigation results with existing research. The majority of the existing literature provides accounts on propeller-wing interactions and comparisons between tractor and pusher configurations in turbo-props, with engine configuration significantly different from this experiment. Other experiments compare both configurations within the frame of noise levels only. Within the time given, it was not possible to find previous work that would focus on comparisons between tractor and pusher configurations in an aerodynamic sense specifically for fuselage and propeller integrated systems.

6.3. Possible Future Work

There are many more interesting experiments that could be conducted if more time was given. The following lists some of them:

- Effect of different propeller sizes
- Different propeller types and pitches
- Test more body sizes
- Effect of wings and tail-fins
- Difference between blunt and streamlined bodies
- Different angles of attack
7. References


[12] Chappell, P.D. Introduction to Installation effects on Thrust and Drag for Propeller-driven Aircraft. ESDU 85015.


8. Answers to Questions

Please explain the details of the propeller mounts. Did the shaft project forward when the propeller was pushing? Was there a hole there?

Ans) The hole was left open. The effect of hole was assumed to be negligible. When we were worried about overheating of the motor, it was found the hole cooled the motor significantly. However, we should have covered the hole to eliminate its effect once it was discovered that overheating was not a problem.

What is the likely effect of separation?

Ans) The effects depend on the location of separation and the size of the model. The earlier separation starts the higher drag is likely to be produced. Separation reduces the amount of energy in the free stream. For the pusher configuration, when the separated flow reaches the propeller, it will be a lower flow speed thus reducing the propeller thrust and efficiency. If the separation starts at the trailing edge, its effects are likely to be smaller than if it started further up-stream. Since most of the thrust of a propeller is generated by the outer third of the blades, separation at the trailing edge of the model would not reduce efficiency by much, as the separated air will flow mostly through the hub region of the propeller.

One of the benefits of the tractor configuration is that it is not affected by the flow field of the body up-stream, therefore able to operate at a higher propeller efficiency.

Explain how "efficiency" is computed.

Ans) It is explained in section 2, Equation 3.

What about plotting pusher/tractor vs. advance ratio? Looks like it might be nearly constant.

Ans) See section 5.6.
What is the weird point at advance ration about 0.58? Was it repeatable? Scatters away from the rest of the data.
Ans) We are not quite sure because we did not repeat the test at the same data point. It seems that the same effect is also present for small pusher, although not as pronounced.

What is the weight of your models? Are the weights comparable to the existing models used on the force balance? This is just to check that the balance is not being overloaded.
Ans) Since the angle of attack was zero, no significant lift was generated. We were only interested in measuring drag. Therefore, even if the lift axis is overloaded, it should not make any difference.

Advanced ratio, could you further explain this parameter.
Ans) It is explained in section 2, Equation 2.

Did you conduct any runs at different angles of attack? Simulate a craft climbing and descending.
Ans) No. It is suggested in the future work section.