Experimental Investigation of a Ducted Propeller

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Abstract
Performance characteristics and velocity field of a ducted propeller in hover and axial flight conditions are investigated experimentally. The duct has a NACA airfoil profile and the propeller is located at the narrowest inner section of the duct which has 0.42 meter diameter. Symmetric and negative cambered profiles are tested. Effect of duct geometry is studied by means of measurements at various flow conditions. Velocity field upstream and downstream of the propeller, axial force acting on each component of the thrust system, rotor speed and torque are measured. Experimental results obtained for bare and ducted propellers are compared.

Nomenclature

C_P Power Coefficient ($P/\rho n^3 D^5$)
C_T Thrust Coefficient ($T/\rho n^2 D^4$)
C_{TD} Thrust Coefficient of duct
C_{TP} Thrust Coefficient of propeller inside a duct
D Duct inner diameter at propeller plane
J Advance ratio (U/nD)
L Duct Length
n Revolutions per second
N Revolutions per minute
P Power ($2\pi nQ$)
Q Torque
T Thrust
U Free-stream velocity
x Axial direction
r Radial direction
η Figure of merit

1. Introduction

At the beginning of the 20th century, ducted or shrouded-propellers have been suggested due to the need for high static thrust propulsion system on V/STOL aircrafts. Duct usage is preferred to prevent propeller the tip losses and, by this way, to achieve higher thrust. Additionally the geometry of duct determines both velocity and pressure on rotor, thus it has a significant effect on propulsion efficiency. Ducted Fan has been widely involved in low-speed and vertical take-off and landing applications.

There are some variables which affect both performance and design of the ducted fan. These variables are related to blade, duct and combined system. Moreover, while a propeller is inserted into a duct, flow structure produces more complicated problems than an open propeller. Both clarifying these problems and gaining more information, systematic experiments were made on several blades and ducts. One of the first significant studies in this area was was carried out by Sacks and Burnell in 1959 [1]. Researchers investigated the effects of blade pitch, propeller and duct shape such as; chord, diameter ratio, duct profile, leading edge radius for static operation (hovering flight) and axial flight. Total force, power, total moment, division of forces and moment, pressure distribution and velocity field were measured in the experimental parts of the research. According to Sacks and Burnell, a good ducted fan is not also a good compressor due to differences between the ducted fan and compressor. The distribution of thrust among the duct and propeller has significance. Experimental studies were compared with theoretical studies and it was shown that the majority of thrust in efficiently ducted fan can be produced on the shroud. Similar research has been conducted by Fletcher [2]. Duct that was made of five circular airfoils was used in his study. These airfoils had same projected area (S=diameter x chord) on the other hand, they had diverse chords and diameters. Researchers tested the effect of angle of attack on lift, drag and pitching moment of ducted fans.

There are more detailed theoretical studies on ducted fan. One of them is Morgan’s [3] research. Linearized circular airfoil theory and lifting line propeller theory were applied for this study. Variables that are formed by interaction between shroud and propeller such as, radial velocity induced by the propeller, duct trailing vortex system and induced drag of the duct, theoretically investigated. To confirm and develop the theoretical research, experimental and theoretical studies were examined in comparison. Kriebel and Mendenhall [4] in 1966 investigated both theoretically and experimentally performance of two full-scale ducted propellers. Difference between experimental and theoretical problem were attributed to dissimilarity of blade loading distribution and the occurrence of flow separation from the inner duct surfaces by researchers. In order to eliminate this problem, it is recommended that information of the flow distribution in and around a shrouded propeller is determined in more detail. Black, Wainasuski and Rochrbach [5] examined performance of shrouded propeller experimentally. Pressure distribution on shroud surface, axial velocity, forces acting on the shroud and propeller were measured apart by changing the lip shape, chord, exit area ratio, propeller location within the shroud, blade tip clearance and propeller blade shape. Similar studies experimentally and theoretically are conducted by Kallman, Kenneth and Goodson [6], Mort [7], Hough and Kaskel [8].

Developments on computer programming provided significant improvements in research of the ducted fan. In 1970, Mendenhall and Spangler investigated performance of the ducted fan first theoretically [9], and then using an advanced computer program [10] in those years. Weir [11] carried out ducted fan study including design and analysis part in 1987. According to the researcher, the effects of duct to the propeller are consisted of increment of induced velocity of the flow around the propeller in forward flight and decrement of propeller tip losses. Design of propeller and duct are also complex because of the many variables thus, it is required to make some assumption simplify in order to facilitate the design process.

In recent years, studies on ducted fan are examined not so widely and have limited variables, due to the complex structure of ducted fan. Leading edge ratio, aspect ratio (chord/diameter) are the variables Dyer [12] studied on small size ducted fan for VTOL aircraft. Dyer investigated aerodynamic specification of ducted fan. Graf [13] investigated similar variables in 2005 by using different duct lip shape. It was observed that leading edge radius has more affect than thickness of airfoil on static thrust of duct. Martin and et all [14] designed, analyzed and researched experimentally ducted fan for hover performance. In experimental part, tip gap effects mostly are investigated. Tip gap effects directly influence the figure of merit of a ducted propeller. In CFD analysis part of Martin’s research 3D individual blade modelling for the standard duct and stepped duct is used. Variables such as; duct angle of attack, exit vane flap length, flap deflection angle and duct chord length are examined for axial and forward flight by Abrego and Bulaga [15]. Researcher showed that high power coefficients are obtained at high advance ratio. As the duct angle of attack decreases, the power coefficient decreases. Additionally flow separation is observed over the duct lip at 5-deg angle of attack. Productive methods of generating duct thrust depend on value of exit vane flap deflection angle and flap chord length. In order to improve performance of ducted fan Ahm and Lee [16] used a computational method. One of the result of their research is that, major fan duct parameter is the diffuser angle. And it is also determined that the fan duct performance is not affected by the inlet geometry at high thrust coefficients. It is required that boundary layer model including viscous effects. Tip clearance effect on performance of the ducted fan is investigated by Martin and Pung [17] in 2004. It is shown that decreasing tip gap between propeller tip and the duct surface increases the total thrust. At low RPM, thrust produced by the duct is not affected directly by the viscous effects in the duct. Moreover isolated propeller produces higher thrust than ducted propeller at low RPM.

Performance of the ducted propeller is researched both experimentally and analytically by Lind and et al [18]. Aerodynamic characteristics of ducted fan for hover and forward flight are investigated by Aktürk, Shavalikul and Camcı [19] using PIV methods. It is shown that, flow over the propeller is symmetric in hover flight. However; separation area is observed ob the leading edge of the ducted fan in forward flight. Thus, flow losses its symmetry, and lack of symmetry also has an influence on total moment and duct exit variables. Same researchers investigated

how tip clearance and flow distribution in duct can affect performance in 2010 [20]. Graf, Flamming and NF [21], Zhao and Bill [22] and Myers [23] are contributed the evaluation of ducted fan systems by similar researches.
In this research, performance of the ducted fan for VTOL UAV is investigated experimentally. Initially, duct with NACA 0018 airfoil is chosen. Then, NACA 0012 airfoil shape is proposed to investigate the effect of thickness ratio. Finally inverse NACA 4312 is used to examine camber effects on the performance. Velocity profiles, axial forces acting on duct and propeller, total thrust of ducted propeller and input power on the propeller shaft are measured.

2. Experimental Setup

Experiments are performed in a 80x80 cm test section open-circuit subsonic wind tunnel of Trisonik Research Laboratory. Wind tunnel provides free stream velocities from 0 m/s up to 20 m/s.
The model consists of a circular duct with a propeller. Although ducts have the same inner radius at propeller plane, thickness ratio, leading edge radius, and exit area ratio of ducts are different. Model parameters are shown in Table 1. A brushless DC electric motor drives two bladed ducted propellers. Motor speed is controlled by an electronic speed control (ESC) system. DC electric motor is powered by a power supply which has 2.5 kW maximum power. Blade pitches effect (8 and 10 inch) is investigated by using two different fixed-pitch propellers. LXEYG7-APC-16x8 thin electric propeller is used.
A Force/Torque sensor system is used to measure drag and thrust forces. Force/Torque sensor measures the full six components of force and torque using a monolithic instrumented transducer. The F/T transducer uses silicon strain gages. Sensing range in measurement direction (parallel to motor axis) is ±80 N and resolution is 0.04 N. Transducer is mounted at the bottom of the motor case nearby the propeller axis to prevent moment overloads. Transducers sensing elements are directly connected to an electronic board located separately because of minimized sensor dimensions. A controller, which communicates over an RS-232 serial port to a PC, processes the strain gage information and outputs analog force/torque data.
Torque applied to the propeller shaft and rotational speed (rpm) is measured by an in-line rotary torque transducer. Measurement range of torque transducer is 0-5Nm and accuracy is %0.5 of full scale. Transducer is placed between electric motor and propeller shaft by using couplings and special fittings.

Table 1: Geometric Parameters of Ducts

Geometric Parameter	NACA 0018	NACA 0012	NACA 4312
Outer Radius	253,6 mm	238,7 mm	235,5 mm
The narrowest inner radius	211,7 mm	211,7 mm	211,7 mm
Aspect ratio (L/D)	0,5	0,5	0,5
Tip gap ratio	0,042	0,042	0,042
Thickness ratio	0,18	0,12	0,12
Leading Edge Radius	17,9 mm	8,4 mm	7,3 mm
Exit Area Ratio	1,099	1,064	1,094

Velocity measurements both in the wake region and inside the duct are performed by using a DANTEC 90C10 constant temperature anemometer. The hot-wire signal was digitized using a 16 bit A/D Board with 16 analog input channels. Sampling rate was set at 16384 Hz and sampling time was about 1s for each measurement point. During the experiments, probe location was controlled by a three directional traverse mechanism. The accuracy of linear motion was 0.016 mm. Both probe traversing and data acquisition processes were controlled by a PC. Schematic diagram of the experimental rig is given in Figure 1.
Detailed measurements for static conditions an also for different free stream velocities (5, 10, 15 and 20 m/s) at low rotor speed conditions are performed by Koc[24].

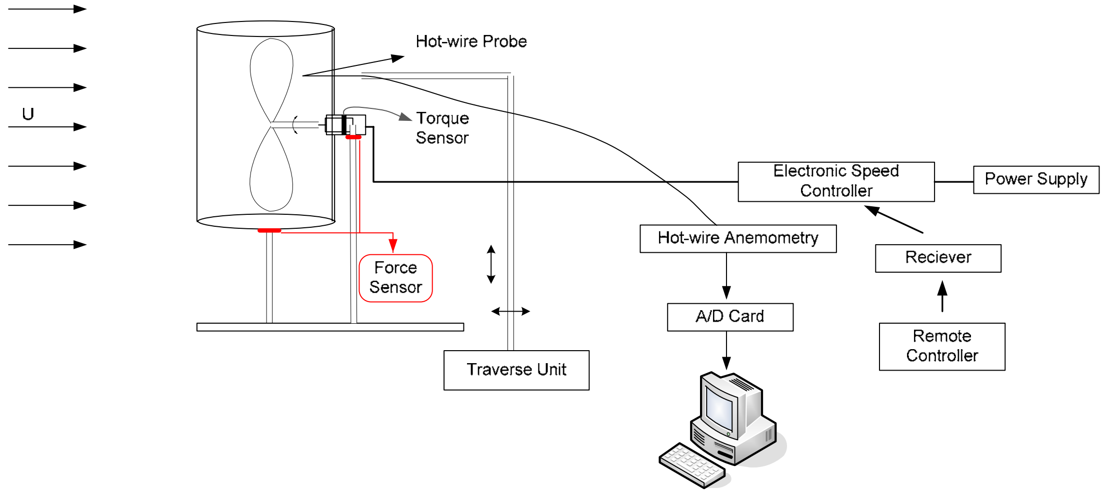

Figure 1: Experimental Setup

3. Experimental Results

3.1 Bare Propeller

Isolated propeller characteristics are investigated in order to be reference and compare with the ducted propeller. Thrust of open propeller and velocity profiles at exit plane are acquired by using force/torque sensor and hot-wire anemometer respectively. Velocity distributions downstream of the propeller were measured at 5 locations (Figure 2). Radial distance is normalized with diameter of the duct at rotor section. As the distance from propeller plane increases, the value of the axial velocity raises and flow field induced by propeller contract. As it is seen also that boundary layer is occurred on the surface of the motor shell.

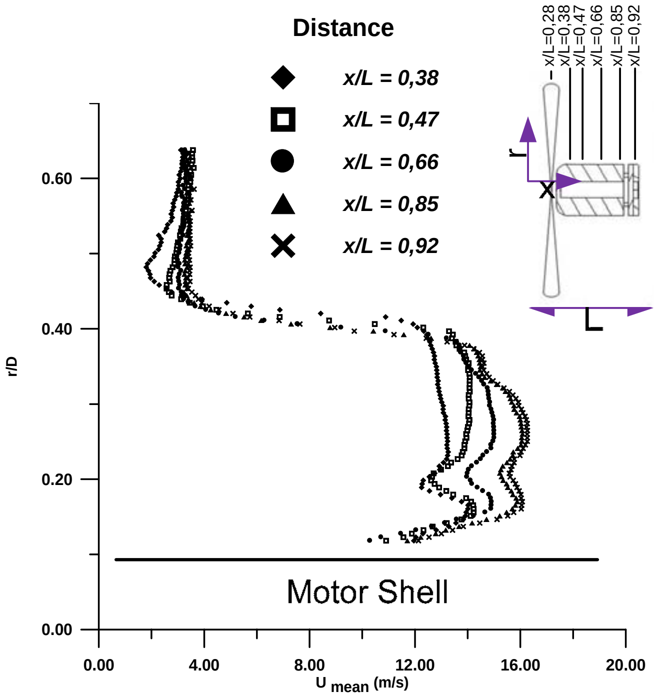

Figure 2: Velocity Profiles at Exit Plane at Static Situation

Axial forces produced by propeller are investigated with different flow velocities and rotor speeds. Advancing the input power of motor provides thrust produced by propeller increase. As expected open propeller has greater thrust in static situation (u=0 m/s). There is an inverse relation between thrust and free stream velocity (Figure 3).

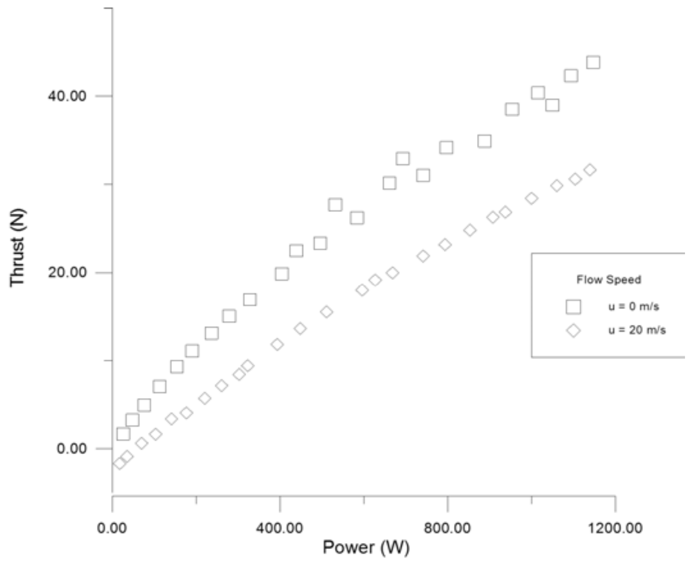

Figure 3: Thrust Produced by Open Propeller

3.2 Ducted Propeller

3.2.1 Axial Force & Torque Measurements

Thrust measurements of a ducted propeller consist of two parts. In the first part, force sensor is mounted at the bottom of the duct in order to examine forces acting on the duct itself. There is no mechanical connection between duct and motor case. These two components are separately supported in the test section. In the second part of experiments force sensor is mounted below the motor case. Hence, thrust produced by propeller is measured.

Duct is oriented parallel to free-stream direction. Propeller locates at the narrowest cross-section of the duct. Experiments are conducted at 5300 rpm and 7000 rpm rotor speeds. Driving power of electric motor is altered so that rotor speed remains constant under different free stream velocity conditions. Torque transducer is utilized to determine propeller power output. Torque applied on the propeller shaft is measured by an in-line torque transducer and converted to power (watts) by multiplying it with the angular speed (rad/s). Axial forces acting on duct and propeller are measured one by one for the dynamic case. Results for 7000 rpm rotor speed are presented in Figure 4. As can be seen from figure duct produces an additional thrust in ducted propeller system. Thrust obtained from the duct decreases with increasing advance ratio. Highest duct thrust coefficients are obtained from inverse NACA4312 profile. Duct causes negative thrust (drag) for high advance ratios. Propeller inside duct; produces slightly lower thrust coefficients than that of an open propeller for same advance ratios. But at low free-stream velocities (low advance ratio) duct geometry strongly affects propeller thrust coefficient. Most effective duct shape is NACA 4312 according to Figure 4.

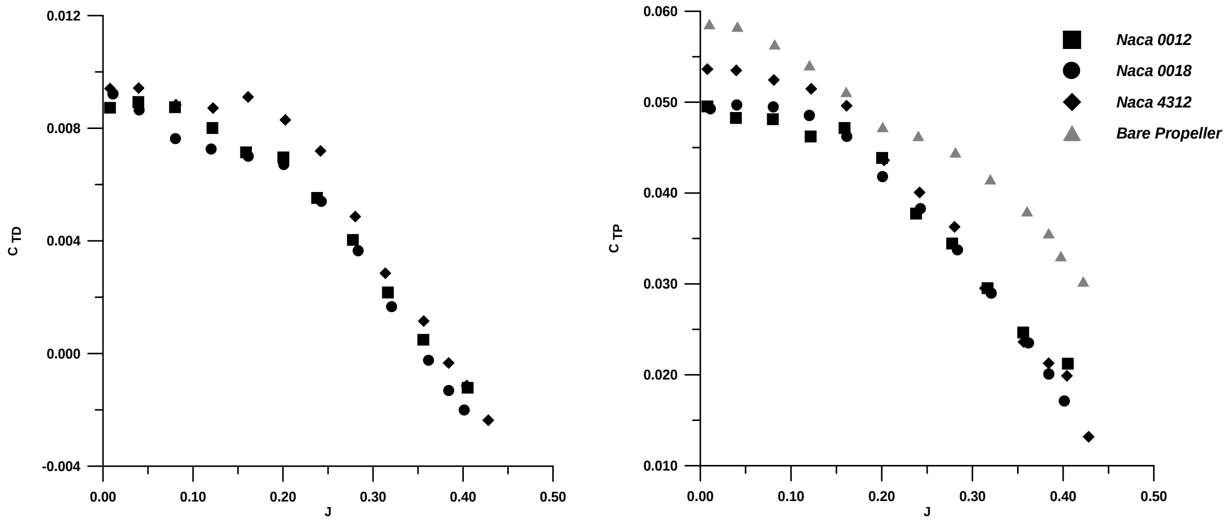

Figure 4: Thrust components produced by duct and propeller (N=7000rpm)

Measurements are repeated at 5300 rpm and compared with previous results in terms of power coefficient and total thrust coefficient in Figures 5 and 6. Therefore, the effects of the duct geometry on thrust system performance are also shown in figures. Ducted propellers require less power than open propeller (Figure 5). It is shown that power coefficient of inverse NACA 4312 shaped duct has the lowest values.

Total thrust coefficients are compared in Figure 6. Higher rotor speeds provides greater thrust. Total thrust of ducted systems at 7000 rpm reach equivalent or higher values comparing with open propeller case in low velocity range. Up to 13m/s flow velocity ducted propeller has greater thrust coefficients according to bare propeller. Again it is shown in Figure 6(b) that NACA 4312 profile has better thrust than other duct profiles and bare propeller at low velocity region. NACA 4312 ducted propeller needs less power to produce same thrust. Consequently, advanced efficiency values are obtained at 7000 rpm (Figure 7).

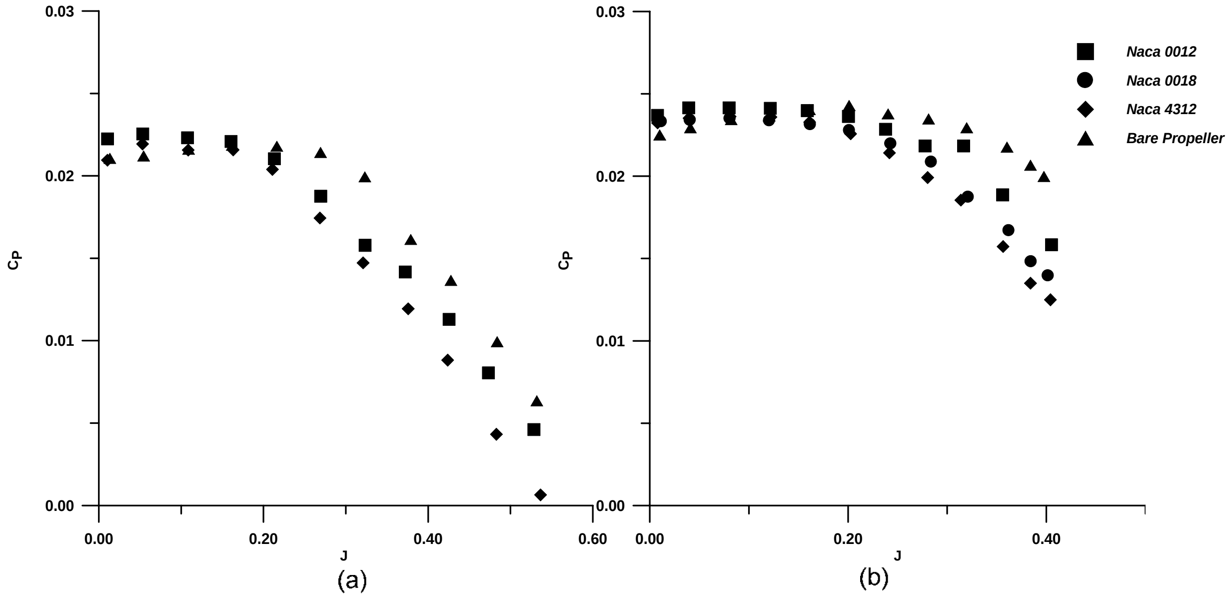

Figure 5: Power Coefficient versus Advance Ratio at (a) 5300 rpm, (b) 7000 rpm

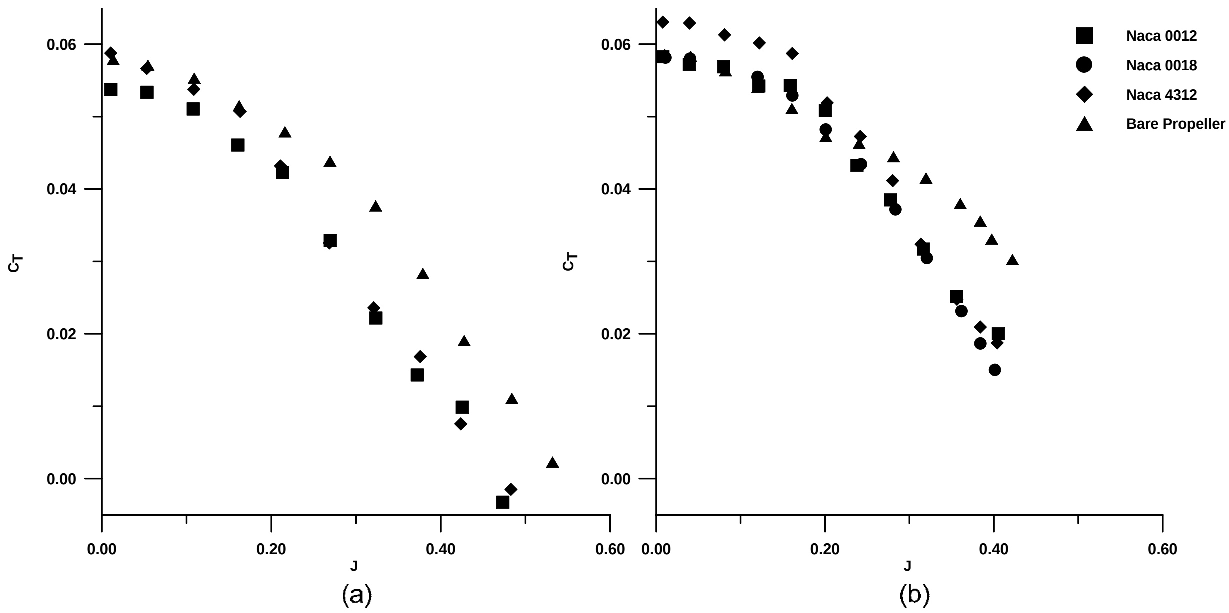

Figure 6: Thrust Coefficient versus Advance Ratio at (a) 5300 rpm, (b) 7000 rpm

As it is observed from Figure 7, NACA 4312 profile has better efficiency according to bare propeller. Up to 15 m/s free-stream velocity, ducted propeller has higher efficiencies than open propeller. Maximum percentage of the augmentation in efficiency according to bare propeller is occurred on NACA 4312 profile. Maximum increment in efficiency is almost %17. Efficiency curves at 5300 rpm rotor speed are given in Figure 8. Insertion of propeller in to a duct results in no remarkable improvement at 5300 rpm rotor speed. Efficiency increment is very low and appears only in a narrow advance ratio range.

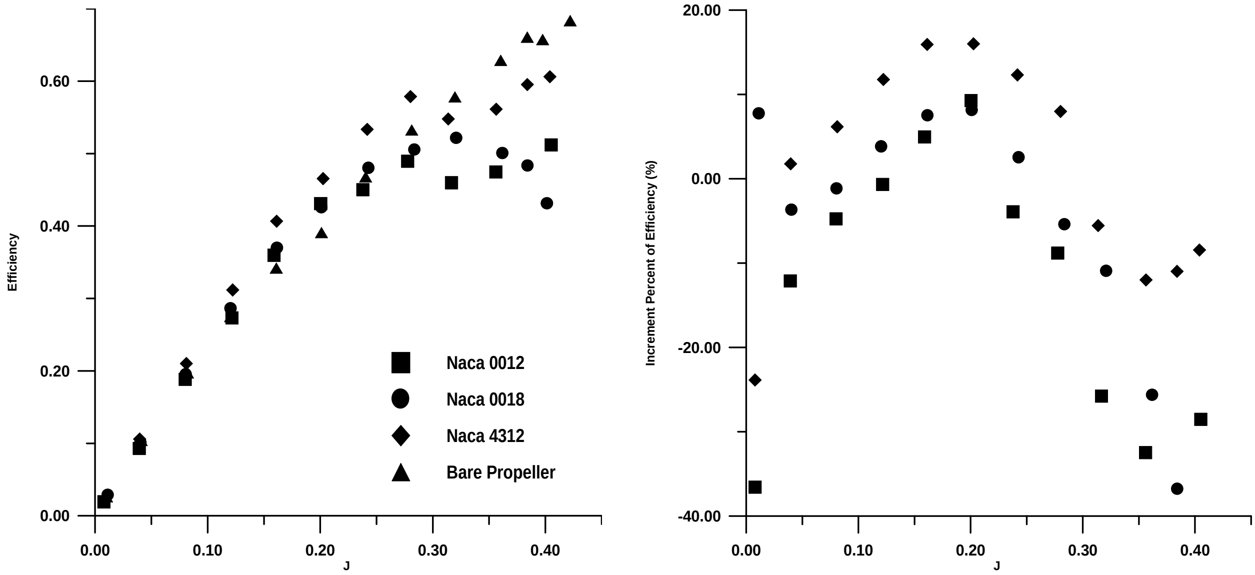

Figure 7: Figure of Merit and % increment of efficiency at 7000 rpm Rotor Speed

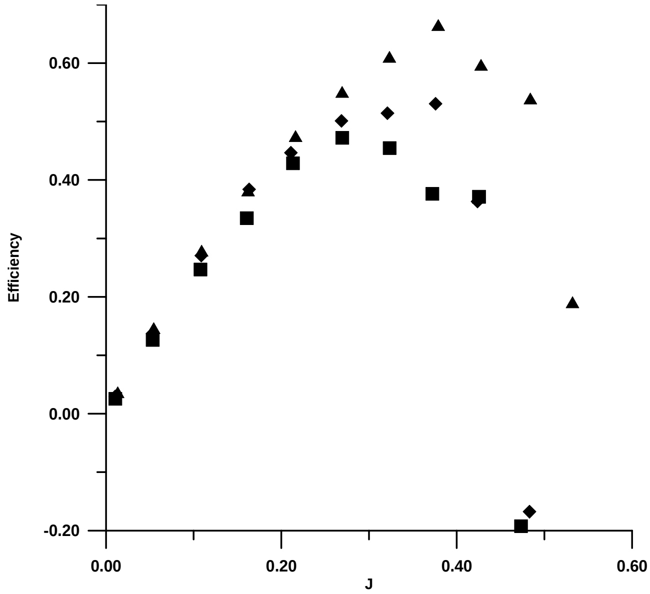

Figure 8: Figure of Merit at 5300 rpm

3.2.2 Velocity field measurements

Velocity profiles at the exit planes (15 mm far from trailing edge) are measured by using hot-wire probe. All duct profiles are tested at 10 and 20 m/s free-stream velocities and results are presented in Figure 9. Radial distance is normalized with duct diameter (D) and velocity values with free-stream velocity. Results are compared with bare propeller velocity profiles in slipstream. According to previous results; measurements at 10 m/s represents the case which the duct yields efficiency augmentation while measurements at 20 m/s characterize the flow conditions where efficiency loss is occurred in the ducted propeller configuration. At low free-stream velocities, both bare propeller and ducted propellers accelerate flow much more. The presence of the duct reduces the slipstream contraction of bare propeller. Hence, velocity profiles at the duct exit plane shows that flow spreads out and effective flow area becomes larger at the exit. Velocity profile close to the duct boundaries has a secondary flow region caused by the tip gap effects.

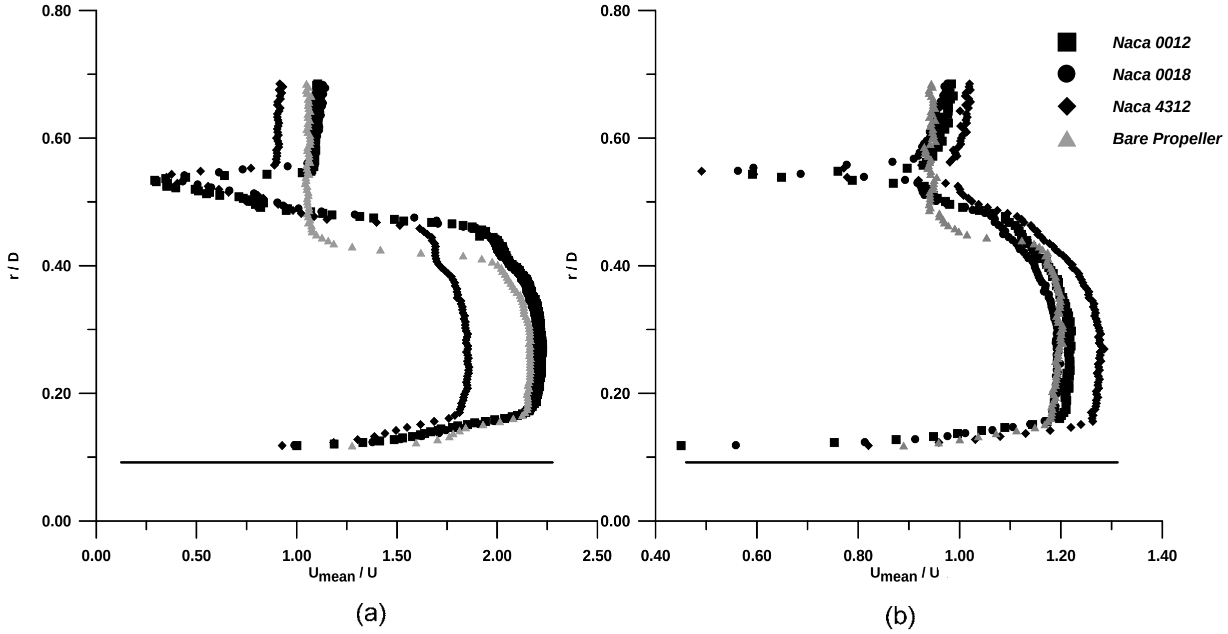

Figure 8: Non-Dimensional Velocity Profiles at Exit Plane, N=7000 rpm (a) U=10m/s , (a) U=20m/s

Velocity profiles at exit plane of NACA4312 duct at different free-stream conditions are presented in Figure 10. Velocities are normalized with maximum velocity measured at the same plane. Velocity profiles approaches to duct boundaries with increasing free-stream velocity.

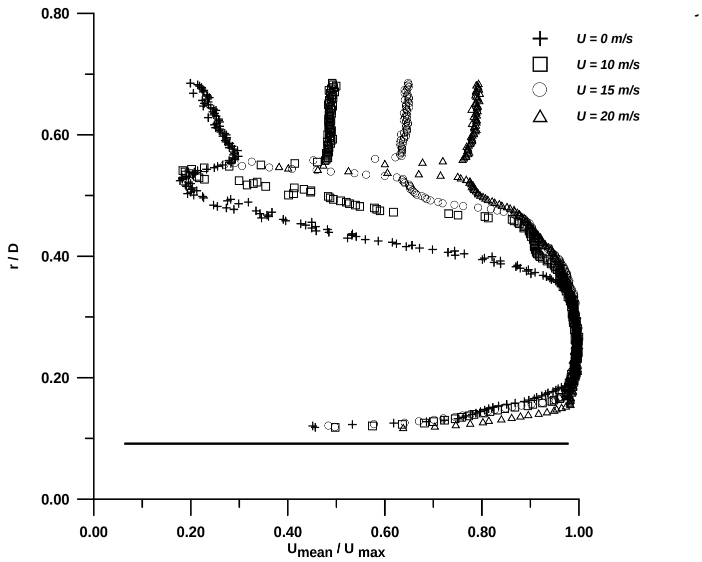

Figure 9: Velocity Profiles at Exit Plane of NACA 4312 Duct N=7000 rpm

Velocity profiles inside the NACA 4312 duct are compared with open propeller velocity profiles in Figures 10 and 11. Just behind the propeller (x/L=0.5), the highest value of maximum velocity occurs. Mass flow through the propeller is increased by the duct. Then, flow decelerates rapidly and low exit velocities at x/L=1.07 are obtained for 10 m/s free-stream velocity. At higher free-stream velocities (Figure 11), axial velocity profiles decelerates with increasing downstream location too. However, deceleration rate is not sufficient and axial velocities at exit plane are superior comparing with open propeller results.

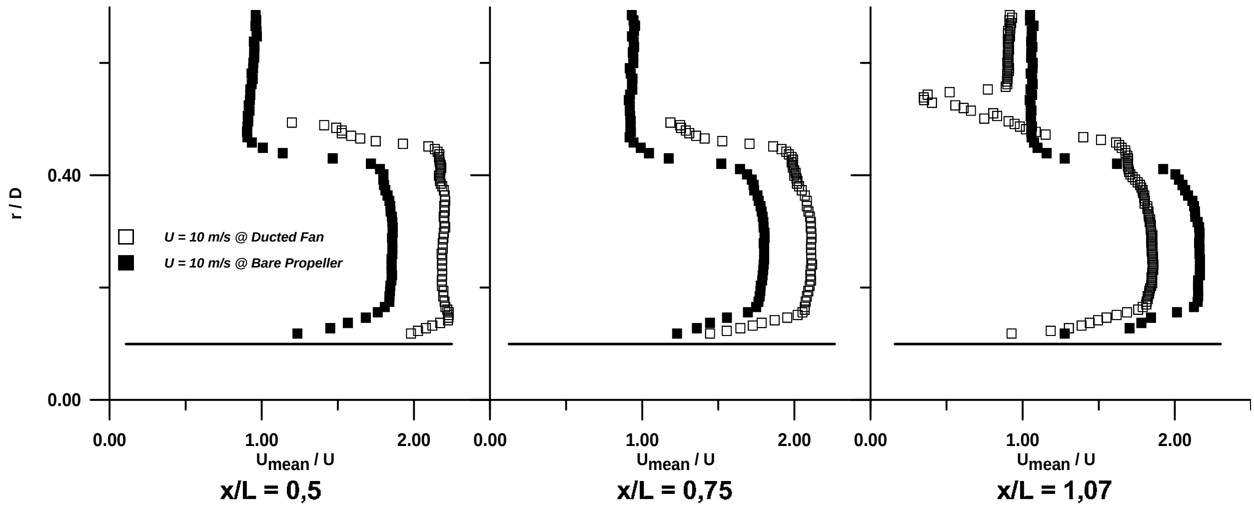

Figure 10: Comparison of Velocity Profiles inside the slipstream of bare propeller and inside duct, N=7000 rpm and U=10 m/s

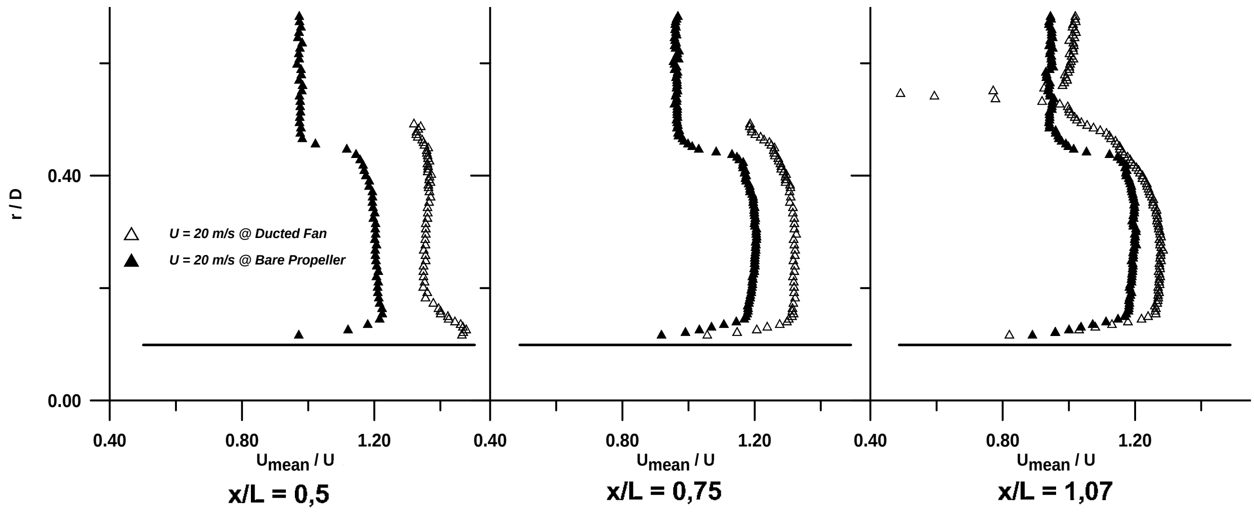

Figure 11: Comparison of Velocity Profiles inside the slipstream of bare propeller and inside duct, N=7000 rpm and U=20 m/s

4. Conclusions

The effect of duct geometry on the ducted propeller performance in axial flight is investigated experimentally. Duct and propeller forces are measured independently. Thrust and power coefficients obtained by using NACA 0012, NACA 0018 and NACA 4312 profiles are compared with open propeller results. Velocity profiles downstream of the propeller are investigated. Experimental results show that;
- Insertion of propeller inside a duct induces suction flow nearby the leading edge of the duct which results in a production of thrust on the duct.
- Duct thrust decreases with increasing advance ratio and becomes negative for $J > 0.35$ for all duct geometries under investigation.
- Although trust produced by the propeller inside a duct is less than the thrust produced by the same propeller without duct, total thrust of ducted propeller system is greater than that of open propeller in low velocity forward flight conditions according to measurements at 7000 rpm rotor speed. Thrust augmentation effect is not recognized at 5300 rpm. Conversely, total thrust decreases at low (5300rpm) rotor speeds.
- Power coefficients obtained for all ducted propeller arrangements are lower than that of open propeller which indicates propeller operates more efficiently inside a duct.
- Eventually, efficiency of ducted propeller system has higher values comparing with bare propeller. Maximum efficiency augmentation (%17) is obtained from NACA 4312 profile at 7000 rpm rotor speed.

Acknowledgement

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References

[1] A. H. & Burnell, J. A. 1959. Ducted Propellers- A Critical Review of the State of the Art, Armed Services Technical Information Agency Report No. ARD-232, Virginia

[2] Fletcher, H. S., 1957. Experimental Investigation of Lift, Drag, and Pitching Moment of Five annular Airfoils, NASA Technical Note 4117, Washington

[3] Morgan, W. B., 1961. A Theory of the Ducted Propeller with a Finite Number of Blades, University of California Institute of Engineering Research, California

[4] Kriebel, A. R. & Mendenhall, M. R., 1966. Predicted and Measured Performance of Two Full-Scale Ducted Propellers, Aerodynamic Problem Associated With V/STOL Aircraft, Symposium Proceedings, and July 1966 Buffalo, New York.

[5] Black, D. M., Wainauski, H. S. & Rohbach, C., 1971. Shrouded Propellers – A Comprehensive Performance Study. Hamilton Standard Division of United Aircraft Corporation, Connecticut

[6] Grundald, K. J. & Goodson, K. W., 1962. Aerodynamic Loads on Isolated Shrouded- Propeller Configuration for Angles of Attack from -100 to 1100. NASA Technical Note D-995. Washington

[7] Mort, W. K., 1965. Performance Characteristics of a 4-foot Diameter Ducted Fan at Zero Angle of Attack for Blade Angles. Ames Research Center, Moffett Field. California.

[8] Hough, G. R., & Kaskel, A. L., 1965. A Comparison of Ducted Propeller Theory with Bell X-22A Experimental Data. Air Program, Office of Naval Research, Washington.

[9] Mendenhall, M. R. & Spangler S. B. 1970. Theoretical Study of ducted Fan Performance. Ames Research Center, California

[10] Mendenhall, M. R. & Spangler S. B. 1970. A computer Program for the Prediction of Ducted Fan Performance. Ames Research Center, California

[11] Weir, R. J., 1987. Ducted Propeller Design and Analysis. Sandia National Laboratories, New Mexico

[12] Dyer, K. 2002. Aerodynamic Study of a Small Ducted VTOL Aerial Vehicle, Master Thesis of Massachusetts Institute of Technology.

[13] Graf W. E., 2005. Effect of Duct Lip Shaping Various Control Devices on the Hover and Forward Flight Performance of Ducted Fan UAV's. Master Thesis of Virginia Polytechnic Institute and State University, Virginia

[14] Martin P., Boxwell. D., Nygaard. T. & Tung. C., 2004. Design, Analysis, and Experiments on a 10-inch ducted Rotor VTOL UAV. US Army Research, Development, and Engineering Command, Ames Research Center, California.

[15] Abrego A. I. & Bulaga R. W., 2002. Performance Study of a Ducted Fan System. AHS Aerodynamics, Acoustics and Test and Evaluation Technical Specialist Meeting, San Francisco, California.

[16] Ahn J. & Lee K. T., 2004. Performance Prediction and Design of Ducted Fan System. 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, Florida

[17] Martin P. & Tung C., 2004, Performance and Flow field Measurements in a 10-inch Ducted Rotor VTOL UAV, NASA Technical Report, Document ID:20050009943, Ames Research Center

[18] Lind R., Nathman, J. K. & Gilchrist, I., 2006. Ducted Rotor Performance Calculations and Comparisons with Experimental Data, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada

[19] Akturk, A., 2010. Ducted Fan Inlet/Exit and Rotor Tip Flow Improvements for Vertical Lift Systems. Doctor Thesis of the Pennsylvania State University, USA.

[20] Akturk A. & Camci C., 2010. Influence of Tip Clearance and Inlet Flow Distortion of Ducted Fan Performance in VTOL UAV's. American Helicopter Society 66th Annual Forum, Phoenix.

[21] Graf, W., Fleming & Ng, W., 2008. Improving Ducted Fan UAV Aerodynamic in Forward Flight.46th AIAA Aerospace Sciences Meeting and Exhibit. Reno Nevada

[22] Zhao, H. W. & Bil. C., 2008. Aerodynamic Design and Analysis of a VTOL Ducted-Fan UAV. 26th AIAA Applied Aerodynamics Conference. Honolulu, Hawaii

[23] Myers, L. M., 2009. Aerodynamic Experiments on a Ducted Fan in Hover and Edgewise Flight. Master Thesis in the Pennsylvania State University. USA

[24] Koc, S. T. , Experimental Investigation of Ducted Propeller Designed for UAV, Master Thesis in the Istanbul Technical University Institute of Science & Technology, Turkey