Tip Clearance Effects on the Performance of Ducted Fan

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***Abstract*—Currently, a new generation of ducted fan UAVs (Unmanned Aerial Vehicles) is under development for a wide range of inspection, investigation and combat missions as well as for a variety of civil roles like traffic monitoring, meteorological studies, hazard mitigation etc. The current study presents extensive results obtained experimentally in order to investigate the tip clearance effects on aerodynamic characteristics of a ducted fan for small UAV systems. Three ducted fans having different tip clearance gap and with same rotor size were examined under three different yawed conditions of calibrated slanted hot-wire probe. Three-dimensional velocity flow fields were measured from hub to tip at inlet and outlet of the ducted fan. The analysis of data acquired by the calibrated slanted hot-wire anemometer were done by PLEAT (Phase locked Ensemble Averaging Technique) and three non-linear differential equations were solved simultaneously by using Newton–Raphson numerical method. Flow field characteristics such as tip vortex and secondary flow were confirmed through axial, radial and tangential velocity contour plot. At the same time, the effects of tip clearance on axial thrust were also investigated by using wind tunnel measurement system. For enhancing the performance of ducted fan, tip clearance level should be best optimized.**

***Index Terms*—Ducted fan, inclined hot-wire, thrust, velocity flow field and tip clearance**

I. Introduction

Current research development in engineering systems has spurred interest in finding new solutions for military and civilian missions. One of the solutions is unmanned aerial vehicle (UAVs) [1]. The applications are mainly a wide range of inspection, investigation and combat missions as well as for a variety of civil roles like traffic monitoring, meteorological studies, hazard mitigation etc. The merits of these vehicles are small size, less weight and low operation cost etc. Present research surveys have exposed that marvelous amount of research is being carried in the area of design and development of UAVs especially for above mentioned missions. However, most of it is focused on designing and development of conventional fixed wing configurations whereas rotary wing vehicles have considerable advantages over fixed wing vehicles for these types of goals mainly when the vehicle is required to remain stationary (hover).

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Like, monitoring and intelligence gathering within or around the buildings requires hovering vehicles with better stability characteristics. Deployment of duct augments thrust by 30 to 35 % more than what is produced by without duct, open rotor of same diameter. This idea offers potential advantages for micro class air vehicles where every additional gram in total weight of vehicle plays dominant role in overall performance especially in hover condition. The duct around rotor has multi-functions such as it supports rotors, produces a portion of the thrust and reduces noise etc. This design also enhances safety for operations in restricted areas by protecting the rotor from tip strikes.

In research of turbo machinery such as turbines, ducted fans, compressors, and propulsion pumps, there are many key factors that affect the design and performance of these machines. One of the main concerns is that there should be a tip clearance between the rotor and the casing to prevent the physical contact between these two surfaces. However, due to existence of this tip clearance, there is a flow under the blade tip that originates from the pressure difference across the blade tip section and the relative motion between the blade end and the end-wall. This difference in pressure between the pressure and suction surfaces drive the flow through the tip gap region of a turbo machines. Upon exit from the tip clearance, the flow meets with the flow from the blade passage and rolls up to generate the tip leakage vortex. This tip clearance flow is tremendously complicated because it forms in the presence of a potential core, secondary flow, the end walls boundary layer, and the blade boundary layer. The relative motion between the rotor and the casing also creates both viscous as well as inviscid interactions that occur near the blade tip [2].

In case of compressors, it is confirmed that overall system performance is strongly dependent upon the pressure ratio and efficiency. It has been experimentally observed that the efficiency loss value is higher by increasing the tip clearance level between the compressor rotor tip and the casing. At the back end of the compressor, where the pressure and density values are the highest, the blade height is the smallest to ensure that the axial component of the average velocity is approximately the same for all stages. This means that the tip clearance level normalized on the blade span is largest in the high-pressure stages. However, the efficiency of these later stages is decreased considerably due to the increase in the ratio of the tip clearance to the blade height. It is also found that the high-pressure differences across the tip clearance region in a compressor cause unsteady loading on the blade tips and thus results in the generation of noise. Therefore, in order to decrease the noise created by this unsteady loading, designer must have a better understanding of the tip clearance flow [3].

One of the addressing issues found in propulsors is cavitation. Cavitation is generated by the rapid collapsing of small low-pressure bubbles in a liquid. Primary source of cavitation has also been observed to be in the tip clearance region. The difference of pressure across the tip clearance causes the generation of cavitation near the suction surface of the propulsors blades. The cavitation has many harmful effects on the blades within the propulsors as well as creating unwanted noise. Therefore, it is required to get rid of the source of the cavitation in order to enhance the life of the propulsors blades as well as to prevent detection of submarines and watercraft [4].

Ducted fan has many of the same flow considerations as those observed in compressors, turbines and propulsors. Rise in thrust produced by ducted fan is due to several factors and aerodynamics characteristics, one of the major reasons is due to small clearance between rotor tip and shroud casing; this reduces rotor tip losses and hence increases rotor thrust. Second reason, upstream and slipstream flows of the rotor generates pressure distribution on duct in such a way that net effect creates more thrust in upward direction. In the case of a given rotor, this extra force can be optimized by varying parameters like size and shape of the shroud, location of rotor along vertical axis and tip clearance [5].

Ducted fans are popular choices in V/STOL unmanned aerial vehicles for a higher thrust / power ratio [6]. Apart from other reason to deploy a duct, major reason is duct-rotor combination provides more thrust than that of open type rotor. Shroud/Duct rotor interaction plays very important role in generating axial thrust. Some of the key issues which need to be addressed before designing and sizing of ducted fans are

i. Tip clearance between rotor and shroud casing. Open rotor has more tip losses due to generation of tip vortices. In case of ducted fans tip losses are minimized due to presence of duct/shroud.

ii. Pressure distribution over duct or shroud is such that it adds into thrust and lift values.

iii. Shape and size of duct or shroud also affects the thrust augmentation.

iv. It also requires to be determined between optimum way to control the direction of vehicle. Either tilting the rotor or thrust vectoring using vanes. Anyway, will result in much more complicated aerodynamics characteristic though both are significantly different configuration [7-10].

A better knowledge of the tip clearance flow through turbomachinery such as turbines, compressors, ducted fans and propulsors will provide a better understanding for designing and development of turbomachinery. Because this tip clearance flow has an extremely significant effect on the performance and efficiency of turbomachinery, it is beneficial to understand the flow phenomena that occur because of the presence of this tip clearance [11].

The eventual goal of this research is to investigate the effects of tip clearance on three-dimensional velocity flow fields as well as thrust produced by ducted fan for small UAV systems. In order to achieve these objectives, three ducted fans having different tip clearance ratio and with same rotor size were examined under three different yawed conditions of hot-wire probe. The tip clearance effects have a considerable influence on three-dimensional flow field and thrust generated by these ducted fans. There have been many numerical studies about the flow in tip clearance region of turbine and compressor, but there have been very few experimental studies about the tip clearance effects on ducted fan aerodynamics characteristics. This article documents the experimental study used to investigate the tip clearance effects and hopefully these results will lead better understanding for fundamentals of the flow through the tip clearance region of ducted fan.

II. Experimental setup

The experimental apparatus, as shown in Fig 1, was set up for investigation of tip clearance effects on aerodynamic characteristics of a ducted fan. Three ducted fans having different tip clearance gap of 1mm, 2mm, and 3mm respectively are examined with the same rotor size of 248mm dia. The detailed specifications of these ducted fans are shown in Table I. The rotor used in the tested fans has 3 blades which are consisted of tip radius of 124mm and hub radius of 29mm as show in Table I. Dimensions of ducts having different value of internal diameter of 250mm, 252mm and 254mm respectively are investigated in this study.

Fig 1: Ducted Fan Tested in AERO Lab

TABLE I
Specification of Tested Fans

Parameters	Fan (A)	Fan (B)	Fan(C)
No. of blades	3	3	3
Tip diameter (mm)	248	248	248
Hub diameter (mm)	58	58	58
Tip clearance (mm)	1	2	3
Duct diameter (mm)	250	252	254
Duct length (mm)	100	100	100

TABLE II

Specifications of the Measuring Devices

Unit	Specifications
Constant Temperature Anemometer (CTA)	Kanomax Model 1011, Multichannel anemometer, Range: 0 ~ 0.5 A Operating resistance :10 Ω Size of unit:1/6 width,7cm
Proximity sensor	Contrinex 420, Housing size:6.5 mm Response frequency:5kHZ Sensing distance :1.5 mm

Constant temperature anemometer (CTA) made by Kanomax model 1011 is used for conducting this research as shown in Table II. Its current range is 0 ~ 0.5 A with operating resistance of 10 Ω maximum. For measuring rpm and location point, Contrinex 420 proximity sensor is used. This sensor has response frequency of 5 kHz with sensing distance of 1.5mm whereas the housing size required for this sensor is 6.5mm.

III. Experimental methods

Three-dimensional flow velocity flow fields are studied by using a single 45° inclined hotwire probe. Many researchers have used the single sensor hot wire system for investigation of three-dimensional velocity flow fields and Reynolds stress.

A. *Configuration of a slanted hotwire probe.*

Geometry of the slanted hotwire probe is shown in Fig 2. Hotwire sensor inclined angle is represented by the unit vector ***A*** slanted at the probe angle θ_o to the X-axis. The probe coordinated X, Y and Z are fixed to the probe, and velocity is denoted by ***V.*** The probe yaw angle θ_y changes its value by turning angle while pitch angle θ_P remains constant as the probe is rotated about its axis. The absolute flow angle α of the sensor is expressed in terms of the angles of $\theta_{o,}$ θ_y and θ_P as given in Eq 1.

$$\cos\alpha = \cos\theta_o . \cos\theta_P . \cos\theta_y + \sin\theta_o . \sin\theta_P \quad (1)$$

B. *Calibration of a slanted hotwire probe*

In this study, velocity calibration of hotwire is done by adopting method of Grande and Kool [12] at sensor yaw angle θ_y of 90° in a wind tunnel with speed of 0 ~ 60 m/s. Turbulence level of open type wind tunnel is 0.13%. By using a non-dimensional form of Kings law, the relation between bridge voltage (E) and effective cooling velocity (V_e) is obtained as shown in Eq 2.

$$E^2 = A + B\,(V_e)^n \quad (2)$$

The values of three coefficients A, B and n are calculated from a velocity calibration data obtained using the hotwire sensor normal to the flow. Whereas the probe yaw angle calibration was done on a wide range of probe angles from -90~90 degrees at fixed values of velocity and angle between probe axis and velocity vector. The ratio of effective cooling velocity and V_e and actual velocity V is expressed in Eq 3 as shown in Fig 2.

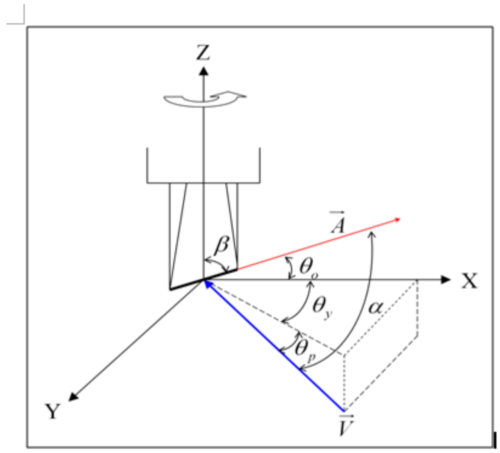

Fig 2: Geometry of a 45° Inclined Hotwire Probe

$$V_e / V = \cos\psi \quad (3)$$

$$Sin\psi = A_2\cos\theta_P \cos\{\theta y/A_1\} + A_2\tan\theta_o \sin\theta_P \quad (4)$$

The experimental velocity and yaw angle calibration results are shown in Fig 3 & 4 respectively and these results are fitted by nonlinear curve fitting method. By the least square fitting of the effective cooling velocity data, the coefficient A, B & n from Eq 2 and A1 & A2 are determined from Eq 4.

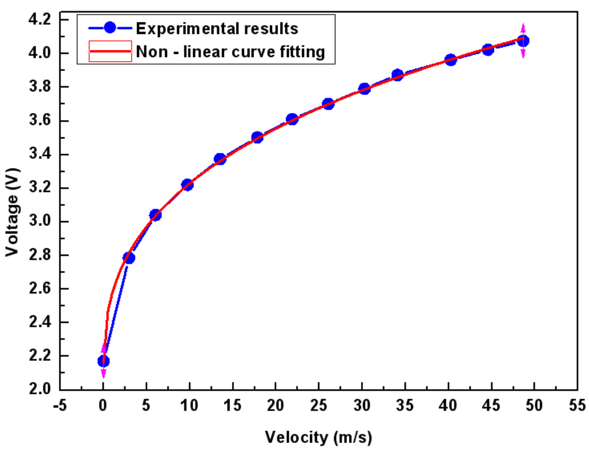

Fig 3: Velocity Calibration

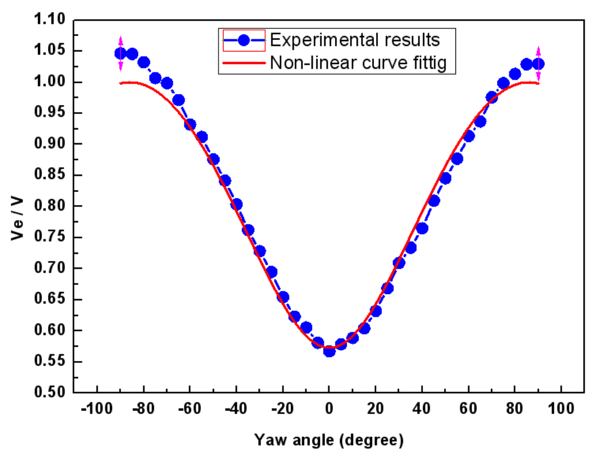

Fig 4: Yaw Angle Calibration

C. Measurement locations and technique

Three-dimensional velocity flow fields for ducted fan were measured at inlet and outlet side at 19 different positions. Fig 5 shows schematic diagram of measuring model with measurement locations. The stationary hotwire techniques were used to the single 45° inclined hotwire probe at three different yawed conditions 30°, 60°, and 90° with the increment of 30 degrees. Velocity flow field is measured at 19 points at inlet and outlet of three ducted fan.

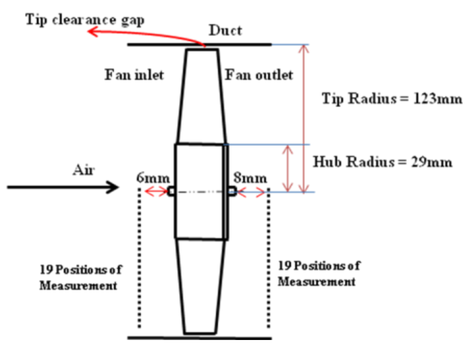

Fig 5: Measuring Points of Flow Fields

Hotwire measurements were made at ducted fans measurement points as shown in Fig 5 by positioning the hotwire sensor and recording data at each of three probe angle orientation. 19 radial locations at inlet and 19 different radial positions at outlet of ducted fans were selected for measuring velocity flow fields. The hotwire was rotated in the flow field to three different positions denoted by a, b and c as show in Fig 5 and 6. These probe positions relate to yaw angles of $\theta_{y,a}$, $\theta_{y,b}$ and $\theta_{y,c}$ which were set as indicated below by Eq 5, 6 and 7.

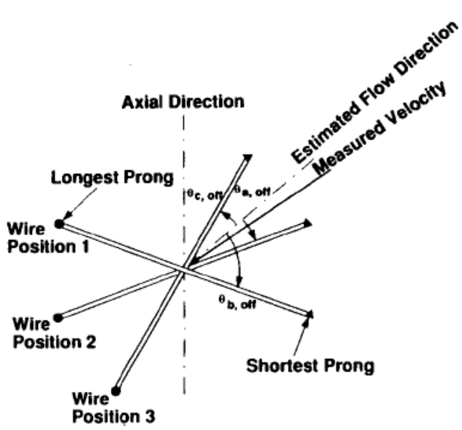

Fig 6: Measuring Locations of Hotwire

$$\theta_{y,a} = \theta_y \quad (5)$$

$$\theta_{y,b} = \theta_y - m_b \quad (6)$$

$$\theta_{y,a} = \theta_y - m_c \quad (7)$$

Where m_b and m_c are in probe turning angle increments from the location. In this study, one position was always close to + 90°. The other two positions were chosen with the increment of 30°. For each orientation of the wire, 800 data samples were taken with a certain A/D speed and arithmetically averaged to obtain a time averaged effective cooling velocity from that particular probe position. For each average measurement of the velocity vector, a total of six nonlinear equations as given below were obtained for the orientation of the wire. The data were averaged by using PLEAT (Phase Lock Ensemble Averaging Techniques) and six nonlinear Eq 8 – 13 were solved simultaneously by using Newton – Raphson numerical methods.

$$V_{e1}^{\ 2} = V^2(1-\sin^2\psi_1) \quad (8)$$

$$V_{e2}^{\ 2} = V^2(1-\sin^2\psi_2) \quad (9)$$

$$V_{e3}^{\ 2} = V^2(1-\sin^2\psi_3) \quad (10)$$

$$\sin\psi_1 = A_2\cos\theta_p\cos\left(\frac{\theta_y}{A_1}\right) + A_2\tan\theta_0\sin\theta_p \quad (11)$$

$$\sin\psi_2 = A_2\cos\theta_p\cos\left(\frac{\theta_y+\theta_1}{A_1}\right) + A_2\tan\theta_0\sin\theta_p \quad (12)$$

$$\sin\psi_3 = A_2\cos\theta_p\cos\left(\frac{\theta_y+\theta_2}{A_1}\right) + A_2\tan\theta_0\sin\theta_p \quad (13)$$

IV. RESULTS AND DISCUSSIONS

The three-dimensional velocity flow fields are measured at 19 points at inlet and outlet of ducted fan by using 45° inclined hotwire probe. The effects of the tip clearance on each type of ducted fan (types A, B, and C) performance have been studied experimentally for same rotor size, and fan speeds of 5000 RPM. Tip clearance was varied from 1mm to 3mm gap. Fig 7a and 7b show effects of tip clearance on velocity flow fields at inlet and outlet of ducted fan ‘A’ having smallest tip clearance gap as described in Table I. The contour plots are colored with the magnitude of velocity. As expected, the magnitude of velocity components i.e., axial, radial and tangential is high as compared to other two ducted fans ‘B’ and ‘C’ type. Moreover, scale of axial velocity component has higher value than radial and tangential component and decreased downstream of axial velocities near the outer wall. The effects of tip clearance are investigated on outlet as well as inlet of ducted fan. In case of outlet, tip clearance effects are more dominant as compared to inlet. Measurement results show that a complex interaction between the rotor tip and duct boundary layer appeared especially at outlet of the duct. Separation of flow is also observed at different points because of some non-uniformity of tip clearance gap due to manufacturing limitations.

Velocity contours plots in Fig 8a and 8b represents velocities at inlet and outlet of ducted fan B having medium tip clearance. Generated contours reveal that velocity magnitude decreased steadily as the tip clearance level enlarged from 1mm to 2mm. Also, behavior of rotor seems to be different by increasing tip clearance gap and the flow pattern near the tip region is also influenced when the tip clearance is increased.

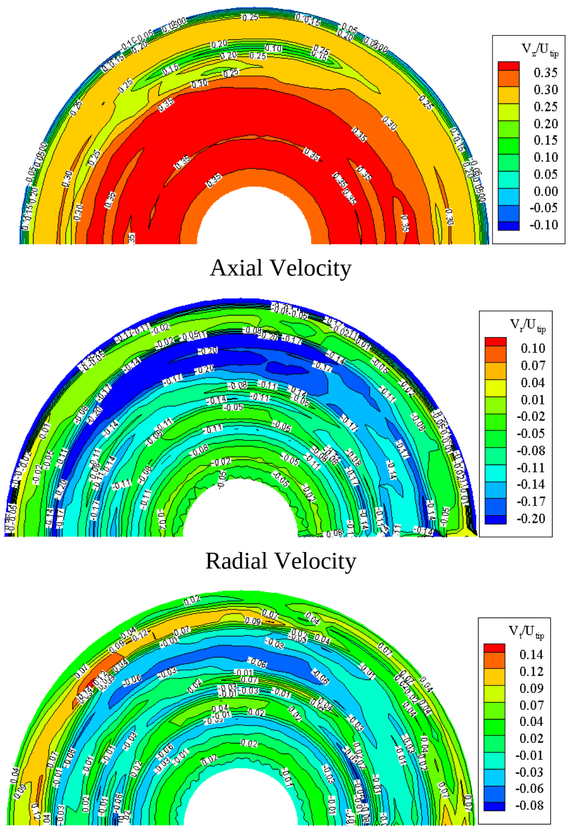

Fig 7a: Non-dimensional Velocity Contours at Outlet of Fan ‘A’

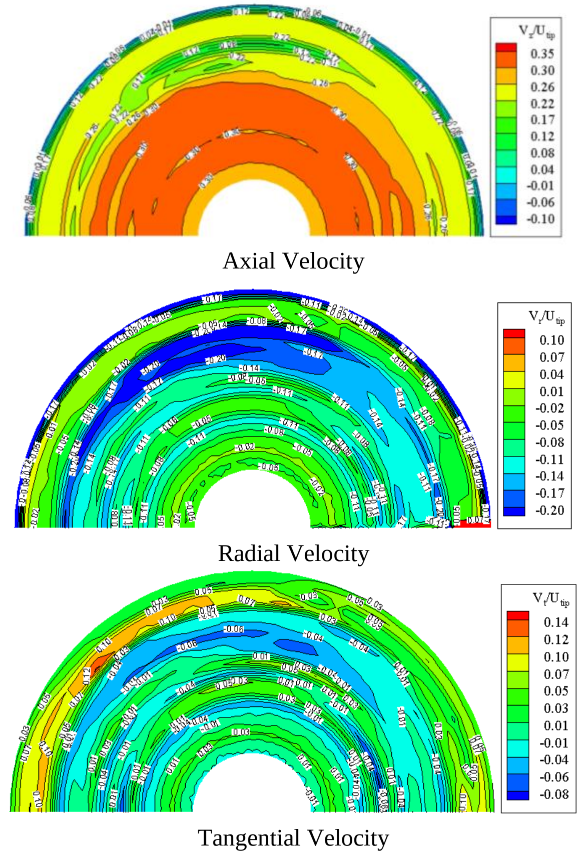

Fig 8a: Non-dimensional Velocity Contours at Outlet of Fan ‘B’

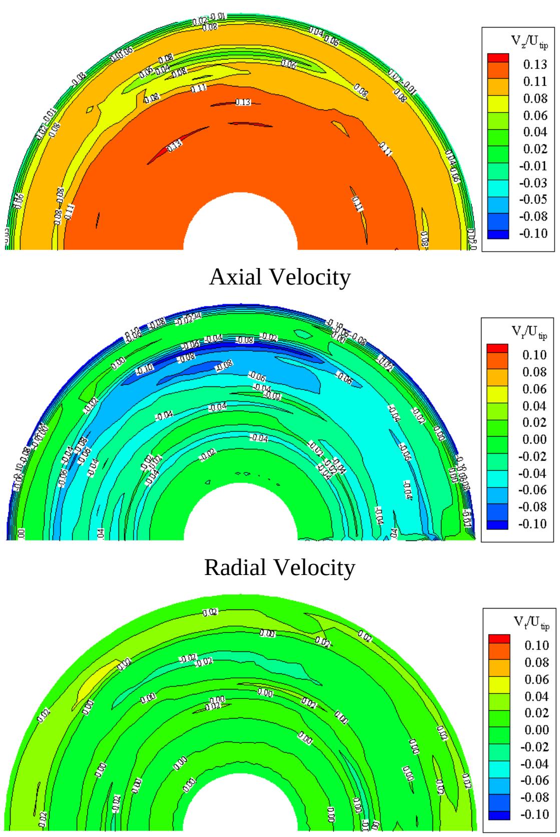

Fig 7b: Non-dimensional Velocity Contours at Inlet of Fan ‘A’

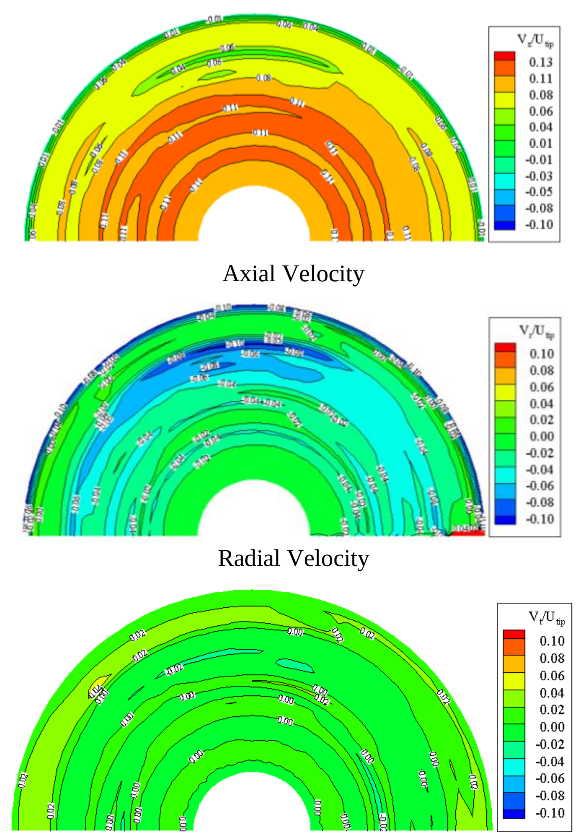

Fig 8b: Non-dimensional Velocity Contours at Inlet of Fan ‘B’

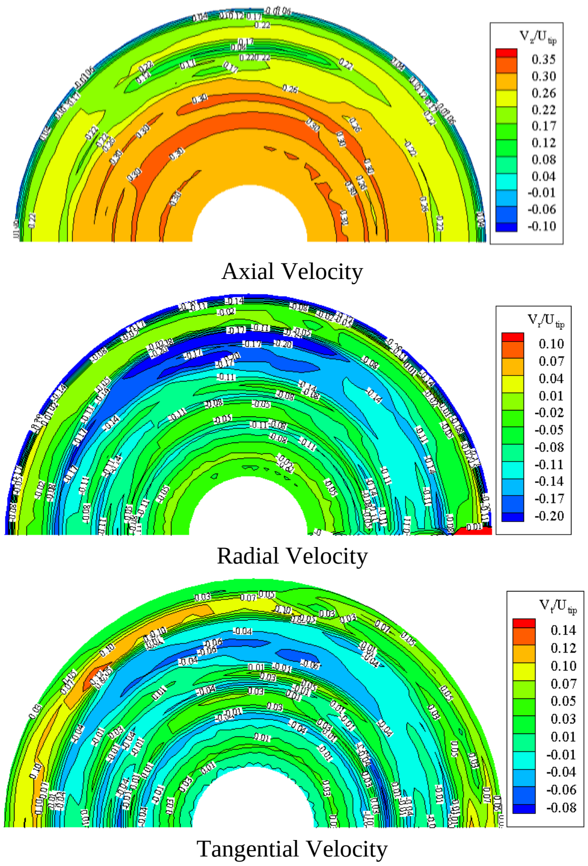

Fig 9a: Non-dimensional Velocity Contours at Outlet of Fan 'C'

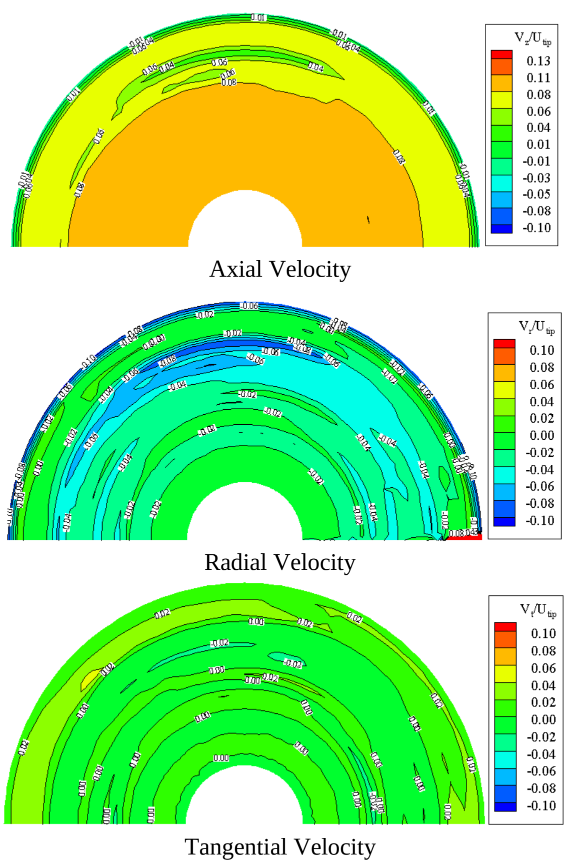

Fig 9b: Non-dimensional Velocity Contours at Inlet of Fan 'C'

Reducing rotor blade height to increase tip clearance had considerable effect on velocity flow field. When the clearance gap is increased from 1mm to 2 mm, the velocity magnitude of all three components seems to be decreased.

Plots of Fig 9a and 9b represent three components of velocity flow fields at inlet and outlet of ducted fan C having high value of tip clearance gap of 3mm. These results generally reveal that total velocity magnitude produced by the ducted fan decreases with the increase of tip clearance in the whole range of flow. The measurements were made at the same locations as made in the previous fan 'A' and fan 'B'. The trend of inflow also plays an important role in magnitude and pattern of exit flow. An increase of the tip clearance level which results an increase of flow area has reduced velocity magnitude as shown in the results of fan 'C'. On the comparison basis of all these results it can be concluded that decrease of tip clearance gap resulted in increasing of axial velocity magnitude more dominantly as compared to other two components of velocity like radial and tangential component.

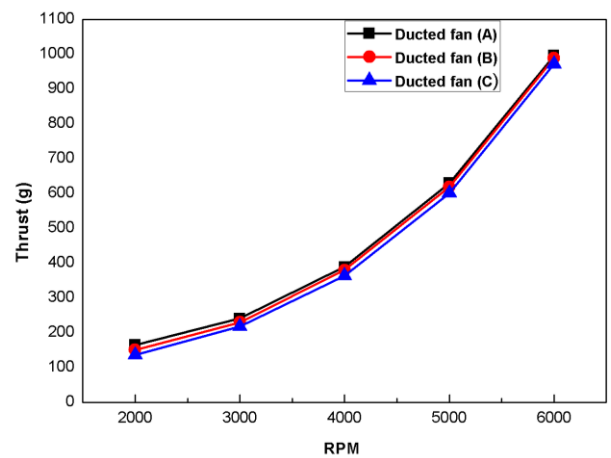

Fig 10: Thrust Variation with RPM and Tip Gap

Another key result of this study was measuring the sensitivity of variation of thrust to increase the tip gap as shown in Fig 10. Since a ducted fan that is usually used for thrusting a small UAV in flight includes a rotor having a plurality of circumferentially spaced apart blades and having a tip spaced radially inward from surrounding. Air that leaks through the blade tip clearance also decreases the efficiency of the fan and resulting thrust. Accordingly, the level of blade tip clearance is made as small as possible to minimize leakage flow without effecting undesirable tip rubs of the blades with the stator shrouds during operation. As expected, the higher value of tip clearance resulted in decrease of axial thrust. By enlarging the tip clearance, the tip leakage flow from higher pressure side to lower pressure side of the blade increase substantially in such fans, which brings considerable thrust losses.

V. CONCLUSIONS

The effects of tip clearance on a ducted fan performance are studied experimentally using three different sizes of ducts with same rotor size and following conclusions are drawn

i. A complex flow interaction between duct boundary layer and rotor tip appeared in all three values of tip clearance gap. In case of exit velocity, this effect is dominant as compared to inlet flow.

ii. Separation of exit flow at outlet of a ducted fan which has higher value of tip clearance gap is more as compared to low level of tip gap because of the pressure difference across the blade tip drives the flow through the tip clearance region.

iii. At a fixed speed of 5000 rpm, the magnitude of all three components of velocity flow fields particularly axial velocity contour have higher value at minimum tip clearance gap.

iv. Measurement results also showed that increasing the rotor tip gap decreased the duct thrust dramatically and therefore can decrease the total figure of merits of the ducted fan.

v. Since tip clearance gap has considerable impact on fan performance characteristics and must be taken into account in the rotor design considerations. However, magnitude and severity of the effects may be quite different, depending on rotor geometry and operating conditions of ducted fan. The efficiency of ducted fan will be continuously improved by reducing the tip clearance level; therefore, it is likely to be concluded that the tip clearance gap should be kept as low as possible.

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