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Experimental Studies for Visualization of Flow with Boundary Layers in an Axial Compressor Fan Inlet using Pressure Probes

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Abstract

Flow at inlet of fan in an axial compressor must be one dimensional as developed flow so that angular momentum fed by the fan to incoming air is maximum. It is possible with good inlet design and optimum inlet length where we obtain stream line flow into fan with nominal boundary layer thickness. Distortion to the flow at fan inlet in an axial compressor is unavoidable problem. For example in aircraft gas turbine engine; flow at inlet of fan is distorted due to maneuvering of air craft, strong cross winds and atmospherics turbulence at inlet of compressor. Flow at inlet of fan affects boundary layer and hence the performance of compressor. Therefore, visualization of flow with boundary layers in an axial ducted fan setup is carried out for well-defined inlet conditions using pressure probes. To visualize the flow with boundary layer development at the fan inlet, static and stagnation pressure are measured throughout the inlet passage of duct using static and pitot probe and velocity is calculated across the given reference planes of duct using Bernoulli's equation. Using these data, profile plots are drawn and mathematical models are developed and flow with boundary layer is analyzed. Under normal inlet flow condition flow in the duct inlet is axisymmetric, steady, turbulent and incompressible. Boundary layer develops consistently towards the fan inlet and it is nominal.

Keywords: Axial Compressor, Boundary Layer, Flow Visualization, Pressure Probes

1. Introduction

Selection of the correct type of intake and the associated inlet geometry has important consequences to any airplane design, military helicopters and ground vehicles which can operate in severe sand/dust environment at high speed. External parameters like aircraft maneuvering, strong side winds and atmospheric turbulence at inlet of compressor will affect the total pressure in an axial compressor inlet. YunusA.Cengel[6] demonstrated the flow field with different types of plots namely time plots, profile plots, vector plots and contour plots. Kwang – Ho KIM[1] represented that measurement of total pressure distribution at upstream and downstream of rotor blade passage can be carried out with specially designed high frequency total pressure probes. J. P. Hulman[7] used pressure probes to measure local static and stagnation pressure. Grey S Setters[8] demonstrated that the visualization of flow patterns is always been critically important in fluid mechanics research field. A single visualization can often lead to more physical understanding than a large set of costly and tedious point measurements. The more complex the flow, the greater the need of visualization to serve as a frame work for correlating other less global but more quantitative observations.Sivapragasam[2] stated that the performance of an aircraft gas turbine engine is affected by the non-uniform or distorted flow in an intake duct, which causes vibration of blades and lowers the surge margin of the engine's compressor system for surge occurring at much lower pressure ratios for all speeds. Kyung-Jae Lee[3] explained that distortion at inlet flow of turbo fan and turbojet engine could cause the surge in the compressor and affect the overall engine operational performance. The special non- uniformity of

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inlet pressure distortion can be caused by shape of inlet, high angle of attack and strong cross winds. B. Yang[4] stated that axial flow compressor or turbines and fans are now playing important roles in civilian and military applications. High performance and low noise are always two important issues in the design of this kind of axial flow turbo machinery. Wei Ye[5] describes how the effect of inlet flow visualization to a turbojet can be evaluated by a distortion model of whole engine, which is based on mass, momentum and energy conversion, and has been proved to be valid tool for evaluating the effects of inlet flow distortion on turbofans. The literature indicates that flow visualization is critical to understand the performance of the compressor. Hence this study aims at visualizing the flow and boundary layer development in an axial flow compressor using a well controlled experimental setup.

2. Experimental Setup and Instrumentation

In this experiment an axial ducted fan setup with bell mouth type of inlet is used since a large part of characteristics for an axial ducted fan is also applicable for an axial compressor. The main differences between the two classes of machines are low pressure, speed and temperature encountered in the ducted fan as compared to the compressor. Therefore to understand the inlet flow characteristics of an axial compressor an axial ducted fan setup is used. Axial ducted fan setup is as shown in Figure 1.

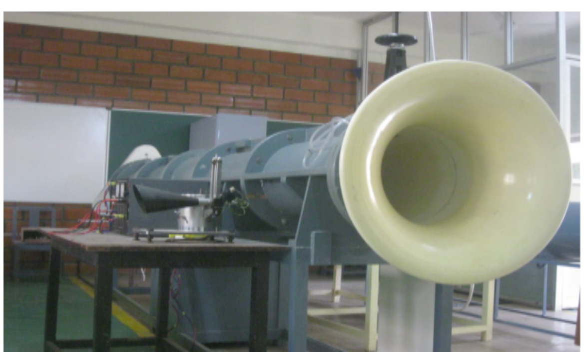

Figure 1. Axial ducted fan setup.

Static pressure is measured through a static pressure tap which is a small hole drilled into a wall of duct such that the plane of the hole is parallel to the flow direction. Static pressure probe is as shown in the Figure 2. Stagnation pressure is measured using a pitot probe which is a small tube with its open end of diameter 0.5 mm which is aligned to the flow such that it has to sense full impact pressure of the flowing fluid. Pitot probes are as shown in Figure 3. Measurement of dynamic pressure is carried out using a digital pressure transducer to which static and pitot probes are connected using capillary tube. This device is calibrated. The pressure transducer is as shown in the Figure 4. Barometer as shown in Figure 5 is used to find atmospheric pressure. Hence atmospheric pressure is also called as barometric pressure. Thermometer which is used to find atmospheric temperature is kept inside the barometric setup.

Figure 2. Static probe.

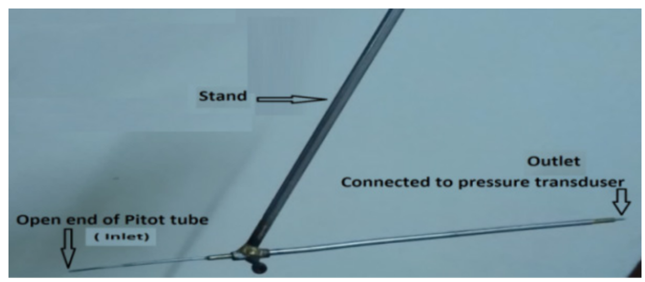

Figure 3. Pitot probe.

Figure 4. Different views of digital pressure transducer.

Figure 5. Mercury Barometer.

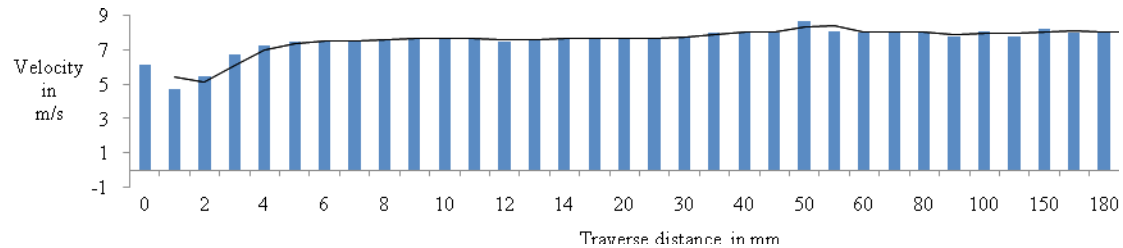

Figure 6. Boundary layer development plot at reference plane 1 for normal condition.

3. Methodology

Study involves creating 1D and 2D stream patterns with boundary layers at the inlet of axial ducted fan to simulate actual flow patterns under uniform inlet flow condition and analyzing work fed by the fan blades to the incoming air at all radii from hub to tip at runner speed 3600 rpm. Hence three reference planes are taken along the inlet duct and named as reference plane one, reference plane two, and reference plane three. These reference planes are normal to the flow direction. At all given points static and stagnation pressure is measured across each reference plane and velocity of air flow is calculated using the Bernoulli's equation $V= \sqrt{[2*(\Delta P)/\rho]}$. For calculated velocities profile plots are drawn and mathematical models are developed using curve fit method by which flow is visualized. Average velocity of air flow is also necessary to calculate the value of free stream velocity, efficiency of fan and type of flow in the duct at inlet of fan. Average velocity between hubs to tip of air flow is calculated by using following integration method.

$$\textbf{Average Velocity} = \frac{1}{b-a}\int_{a}^{b} f(x)\,dx$$

Where a and b are integral limits in terms of mm which is taken from hub to tip of fan.

4. Results and Discussion

4.1 Boundary Layer Development Plots and Velocity Profile Plots for Normal Flow

In this study velocity profile plots and boundary layer development plots are the two views for the same data. It is required to analyze the flow if it is turbulent with adverse pressure gradient.

Figure 6 indicates boundary layer development plot. It is drawn at reference plane one. In this plot distance is measured from bottom of surface to the center of duct. This plot indicates that, velocity reaches freestream value at 5 mm from the surface of duct. Hence thickness of boundary layer is 5mm at first reference plane. By experiment and physics it is shown that boundary layer thickness is negligible in smooth bell-mouth type of entry. Boundary layer thickness has developed negligible thickness of 5 mm from point of entry to first reference plane. Figure 7 is velocity profile plot at reference plane one. The mathematical model of this plot is represented by $F(x) = 7.285549888+0.6051930357 \; X10^{2x}$.This mathematical equation varies exponentially. Average velocity of air between hub to tip is calculated which is 7.60 m/s. This.

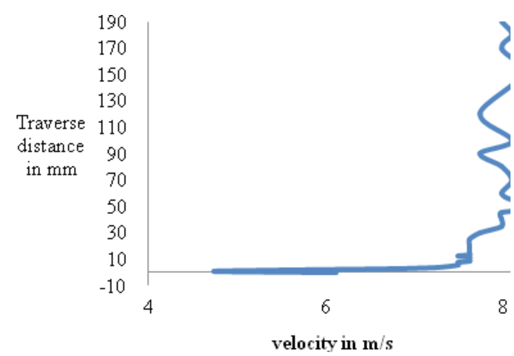

Figure 7. Velocity y profile plot at reference plane 1 for normal condition.

Velocity profile plot shows slight fluctuation in the flow field, but it is almost like one dimensional stream lined flow or developed flow. It is most expected plot as there is no distortion at inlet. Figure 8 shows that, velocity becomes freestream velocity at 10 mm from the surface of duct. Therefore boundary layer thickness is 10 mm at second reference plane.

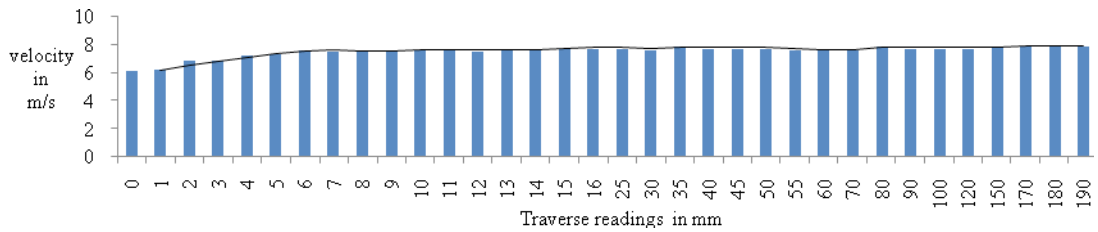

Figure 8. Boundary layer development plot at reference plane 2 for normal condition.

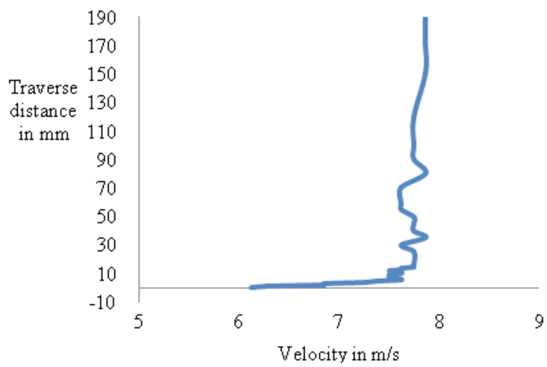

Figure 9. Velocity profile plot at reference plane 2 for normal condition.

Figure 9 is velocity profile plot at reference plane two. The mathematical equation for velocity profile plot which is drawn at second reference plane is F(x) = 7.43786 +0.3291770X10^{2x}.This equation is also in exponential form. Average velocity of air flow from hub to tip is calculated, which is 7.614 m/s. Therefore at second reference plane average velocity has slightly increased than the average velocity of first reference plane. When mathematical equations of first and second reference planes are compared it is observed that both are in the same form. When velocity profile plot of first reference plane and second reference plane is compared, it is observed that fluctuation in second reference plane is less and it indicates flow at second reference plane is more developed than first reference plane. The velocity profile plot is almost one dimensional which indicates streamlined flow (Figure 10).

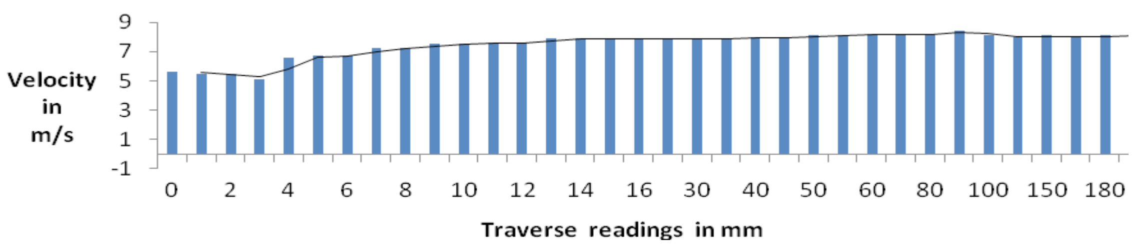

Figure 10. Boundary layer development plot at reference plane 3 for normal condition.

Similarly boundary layer development plot at reference plane three indicates that, velocity becomes freestream velocity at around 13 mm from the surface of duct, therefore boundary layer thickness is 13 mm at third reference plane. At third reference plane velocity profile plot is almost fluctuation free, and it is one dimensional and it indicate flow at third reference plane is almost fully developed flow as shown in Figure 11. The mathematical equation for this plot is F(x) = 7.285149023+0.7102038264X10^{2x}. This equation is also in exponential form. From this equation average velocity from hub to tip of air flow is calculated which is 7.67 m/s and it is slightly greater than the average velocity that is calculated at reference plane one and two. The forms of mathematical equation at all three reference planes are same. In order to find performance of fan and type of flow in the duct inlet for uniform inlet flow conditions the data which are as shown in the Table 1 are calculated.

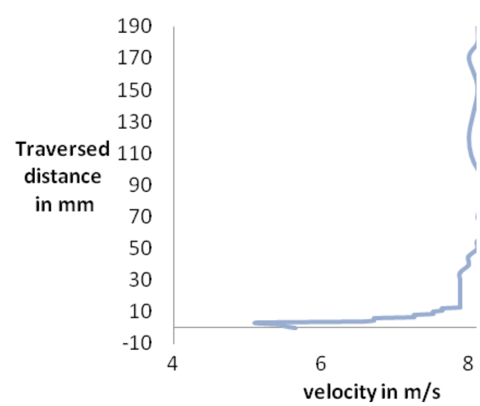

Figure 11. Velocity profile plot at reference plane 3 for normal condition.

Table 1. Calculations for uniform inlet flow

Flow conditions	Fan Static pressure difference in mbar	Average velocity at fan inlet in m/s	Volumetric Flow $\frac{m^3}{s}$	Fan Efficiency%	Reynolds number	Mach number
Uniform inlet flow condition	2.94	7.67	0.69	33.16	1.67 x105	0.023

The mathematical equation is formulated for boundary layer development and this mathematical model is F(x) =1.537012113 + 0.0070947894xwhich is in the form of linear equation that indicates boundary layer develops linearly along the direction of flow.

5. Conclusions

From experimental studies of profile plots, mathematical models and calculated data the following conclusions are drawn.

- Under uniform inlet flow conditions boundary layer thickness is very thin and it increases along the direction of flow and it is nominal.
- For turbulent flow and uniform inlet flow condition, boundary layer develops linearly.
- Flow accelerates slightly towards its direction of motion under uniform inlet flow conditions.
- At fan inlet, flow is free vortex which is almost one dimensional as developed flow from hub to tip under given experimental conditions.
- Flow in the duct inlet is axisymmetric, steady, turbulent and incompressible.
- For turbulent flow profile plots vary exponentially which indicates the form of velocity variation across the duct.

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