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An assessment of NASA Glenn's aeroacoustic experimental and predictive capabilities for installed cooling fans
Part 1: Aerodynamic performance

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ABSTRACT

Driven by the need for low production costs, electronics cooling fans have evolved differently than the bladed components of gas turbine engines which incorporate multiple technologies to enhance performance and durability while reducing noise emissions. Drawing upon NASA Glenn's experience in the measurement and prediction of gas turbine engine aeroacoustic performance, tests have been conducted to determine if these tools and techniques can be extended for application to the aerodynamics and acoustics of electronics cooling fans.

An automated fan plenum installed in NASA Glenn's Acoustical Testing Laboratory was used to map the overall aerodynamic and acoustic performance of a spaceflight qualified 80 mm diameter axial cooling fan. In order to more accurately identify noise sources, diagnose performance limiting aerodynamic deficiencies, and validate noise prediction codes, additional aerodynamic measurements were recorded for two operating points: free delivery and a mild stall condition. Non-uniformities in the fan's inlet and exhaust regions captured by Particle Image Velocimetry measurements, and rotor blade wakes characterized by hot wire anemometry measurements provide some assessment of the fan aerodynamic performance. The data can be used to identify fan installation/design changes which could enlarge the stable operating region for the fan and improve its aerodynamic performance and reduce noise emissions.

1 INTRODUCTION

Cooling fan design, installation, and performance are closely intertwined, making it difficult to identify remedies to system problems. Since disappointing cooling fan aerodynamic and acoustic performance is most often discovered late in a product design cycle, changes to both the installation and the fan design are often difficult or impossible.

With the abundance of cooling fans in use today, both in consumer electronics as well as in spaceflight hardware, it would be easy to assume that electronics cooling fans have reached their evolutionary potential—especially given the advances made in the aerospace industry. Slight similarities in geometry between the aerospace fan and the electronic cooling fan, though, mask large differences in design maturity.

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Driven to minimize operational costs, the aircraft engine industry has taken great pains to maximize aerodynamic efficiency while simultaneously reducing noise. Aircraft engine noise reduction has been a national priority since the 1960's when jet engine powered civilian airliners became common. Cumpsty[1,2] provides a very complete review of early noise research while Envia[3] focuses on more recent fan noise research. Cumpsty[2] notes that extensive aerodynamic development has left gas turbines with very little separated flow and thus less room for improvement however, "For non-aeronautical applications there is more chance of spectacular reductions in noise with improvements in aerodynamics…"

Aerodynamic and acoustic design of cooling fans has suffered from the market demand for minimal production costs. There have been attempts to apply aerospace flow field measurements/analysis and noise source identification to cooling fans. For example, Washburn and Lauchle[4] give a good overview of inlet flow conditions and tone noise generation in low speed fans. In the 1990's Digital Particle Image Velocimetry was used by Estevadeordal, et al.[5] to map the flow field of a forward swept automotive fan to study the aerodynamics. Wang and Huang[6] is another example of fan inlet modifications to reduce noise. This list is by no means complete. However, even with the increased effort in cooling fan aerodynamics the technological maturity of the devices still significantly lags the aerospace industry (See Mann[7]). Cory[8] also makes a strong plea for a greater understanding of fluid dynamics in the cooling fan sector so that better efficiencies (and acoustics) can be achieved.

NASA Glenn Research Center has extensive expertise in the areas of performance and acoustics measurements which complements equally significant expertise in the development of numerical prediction tools which, for aerodynamics, range from 1D meanline analysis to unsteady, 3D, Navier-Stokes solvers. The acoustic prediction tools, likewise, range from simple codes useful in estimating fan tone and broadband noise for conceptual design work to more complex analysis codes that use computational fluid dynamics solutions and accurate, complete geometry descriptions to generate noise predictions.

The purpose of this work is to use aerospace diagnostic tools to analyze the design maturity of electronics cooling fans. A small axial cooling fan was tested with and without an inlet duct. Using cooling fan industry standardized techniques, the fan aerodynamic and acoustic performance is characterized. Two operating points were selected for more detailed measurements using techniques that have been developed to identify performance issues in aircraft fans. Part 1 of this report will demonstrate how the detailed flow field measurements help to explain the limited stable operating range of the fan and the gains in performance due to the addition of an inlet. A detailed discussion of the acoustics is contained in Part 2[9].

2 TEST FAN DESCRIPTION AND COMPARISON

The subject fan is an 80mm commercially available axial cooling fan that is on a list of spaceflight qualified fans compiled by the Acoustics Working Group managed from the NASA Johnson Space Center. A front view of the test fan is shown in Figure 1 and important design/operating characteristics are in Table 1 and are compared to values for an aircraft fan stage[10]. The simple inlet duct used was one fan diameter in length (80mm,1D duct).

An examination of several design features is useful in studying the differences between the cooling fan design and a typical aerospace fan. There are significant differences between the cooling fan and aerospace fan inlets. First, the cooling fan case contains a partial inlet bellmouth shown by arrows in Figure 1. Such geometric discontinuities are avoided in the design of aircraft fan inlets which are used to condition the flow entering the fan in an attempt to provide a circumferentially uniform velocity distribution at the fan blade leading edge. Spatially non-uniform inlet flow to the rotor may create a tone noise source.

Second, the cooling fan has a large hub and no spinner to guide the flow into the rotor root. In contrast, aircraft fans typically have low hub/tip ratios so that they present a large frontal area for flow capacity and the blades operate outside of the hub and casing boundary layers for most of their span to boost performance. The cooling fan geometrical features seem to be driven by the need to accommodate a particular motor design.

Figure 1: Front view of test fan. Arrows show inlet regions where the rotor tip is uncovered.

Table 1: Cooling fan operating and design parameters compared to an aerospace fan.

	Cooling Fan	Aircraft Fan Model
Casing radius	38 mm	279.4 mm
Tip radius	37 mm	278.9 mm
Hub radius	26 mm	83.8 mm
Hub/Tip ratio	0.70	0.30
Operating speed	3,300 rpm	12,657 rpm
Tip speed	12.8 m/s	370 m/s
Clr Height	1 mm	0.5 mm
Blade Chord	34 mm	94 mm
Clr/Chord	2.9%	0.5%
Solidity	0.86	1.7
Rotor blades	5	22
Struts/stators	4	54

Thirdly, the cooling fan clearance/chord ratio is very large. The large clearance/chord ratio, coupled with a case design that leaves the first third and last eighth of the fan blade uncovered in regions, limits the useful operating range of the fan for both pressure rise and flow capacity. Lastly for an application where pressure rise is needed the fan solidity is too low and additional rotor blades are needed for optimal performance.

Interaction tone noise has been the most widely studied aspect of fan and compressor noise. Tone noise is generated in several ways: a rotor interacts with stationary non-uniformities such as the wakes or the potential field of stators and struts, the rotor wakes strike downstream stators/struts, the rotor ingests inlet distortions due to a bad installation, or the rotor ingests turbulence. Contemporary turbofan engines do not have struts or inlet guide vanes thus eliminating incoming wakes to the rotor. Outlet guide vanes are typically 1-2 rotor chords downstream of the rotor trailing edge. This large spacing reduces potential field interactions and minimizes rotor wake/stator or strut interactions. Additionally the outlet guide vanes can incorporate sweep and lean to further reduce tone noise. For fans operating in narrow annular ducts, the rotor/stator blade counts can be chosen so that the blade passing tone is ‘cutoff’ or non-propagating in the duct. Fan inlets are carefully designed to provide circumferentially uniform flow at the fan face over a wide variation of operating conditions. With an engine stationary on the ground or for land based machines, the ingestion of anisotropic turbulence is a significant tone noise source. For ground based noise testing the inclusion of a large bulbous screen over the intake bellmouth, called an inflow control device (ICD), is now standard practice to reduce the non-uniformities in the incoming flow.

Generation and control of broadband noise in fans is much less understood. The two hypothetical generation mechanisms are fan interaction with flow turbulence and noise from self generated unsteady flow in the blade passages[11]. This implies that a high turbulence level in the hub boundary layer, casing boundary layer or tip clearance flow would be a possible sources of broadband noise. For example, an increase in tip clearance height was shown to increase noise by Kameier and Neise[12]. Separated flow is also characterized by high levels of broadband noise. Throttling a fan at a constant speed will often result in increased broadband noise as the blade loading increases with a sharp increase in broadband noise when stall and massive flow separation occur. In aircraft fan design the number of rotor blades (fan solidity) is chosen so that the blade loading is reasonable to prevent separated flow on the blade surfaces.

3 EXPERIMENTAL SETUP

Aerodynamic performance and acoustic measurements were acquired for the cooling fan in the Glenn Acoustical Testing Laboratory (ATL) in accordance with ISO10302[13]. All measurements were done for a constant fan speed of 3300rpm. For this paper results from a 'clean inlet' case and from a 1D duct inlet case are presented. Figure 2 shows the duct attached to the fan inlet. The internal diameter of the duct matched the fan casing diameter and the duct extended one fan diameter upstream of the fan. The duct had a wall static tap installed 13 mm upstream of the fan face. The static tap allowed the pressure rise across the fan to be measured so that the fan was not penalized for the static pressure loss associated with accelerating flow into the duct.

The Particle Image Velocimetry (PIV) and Hot Wire Anemometry (HW) tests were completed in other NASA Glenn laboratories with the fan mounted on a plate. The fan tach signal was used to phase lock measurements to the rotor position. In the PIV tests, 200 image pairs were acquired, converted to vector fields and averaged to produce the flow field velocity contours. To ensure uniform flow seeding the PIV testing was done with the fan/plate assembly mounted in an overturned aquarium, as shown in Figure 3. The inlet and exit flowfields were measured for the free delivery condition and for a mild stall condition. To throttle the fan, a duct was mounted to the fan exit with an orifice plate attached to the duct exit. The orifice geometry mimicked the exit port geometry of the automated fan plenum (Maling box) for an operating condition for where the fan was in mild stall.

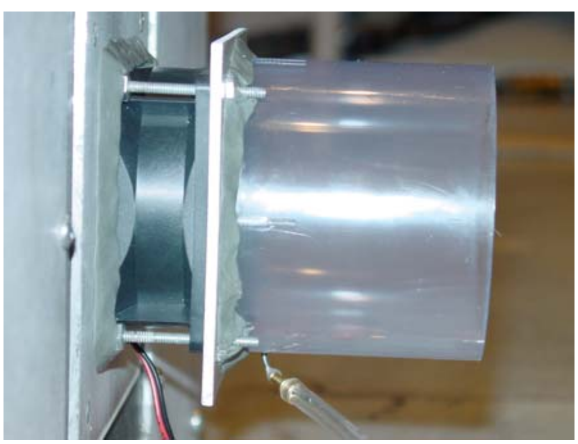

Figure 2: Fan with inlet duct installed. Wall static tap is shown in lower duct wall.

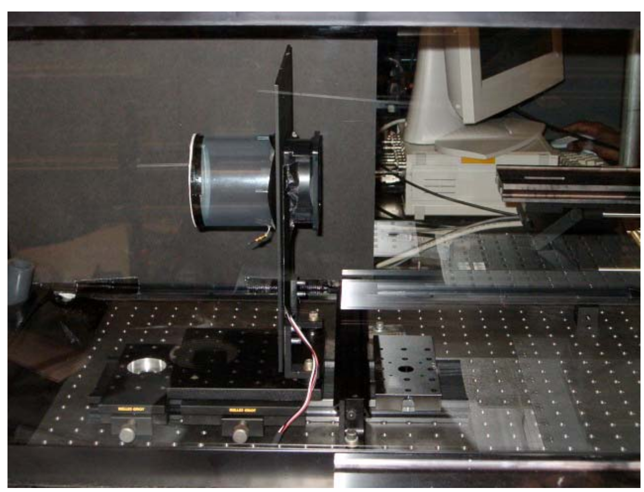

Figure 3: Fan mounted on plate and enclosed in aquarium for PIV measurements. The fan exit duct/orifice is installed to throttle the fan into a mild stall condition.

Hotwire measurements were acquired along a radial line 45 degrees from top dead center between the fan exit struts. The measurement is directly downstream of a partial bellmouth cutout in the inlet. The axial location of the measurement plane is approximately the strut leading edge (see figure 5). Twenty seconds of data at 50kHz sample rate were acquired and phase averaged to produce the average passage data.

4 AERODYNAMIC AND ACOUSTIC PERFORMANCE

Figure 4 shows the aerodynamic performance and overall sound power for the cooling fan with a clean inlet and also for the 1D inlet duct installed. The data have been spline fit. The performance curve for the clean inlet case (circle symbols) shows the typical rise in pressure as the fan is throttled and reaches a local maximum at 42 m^3/hr flow. For axial fans this pressure plateau is an indication that the fan has reached its maximum pressure rise and is on the verge of stall. This operating point is typically near the maximum static efficiency condition for the fan.

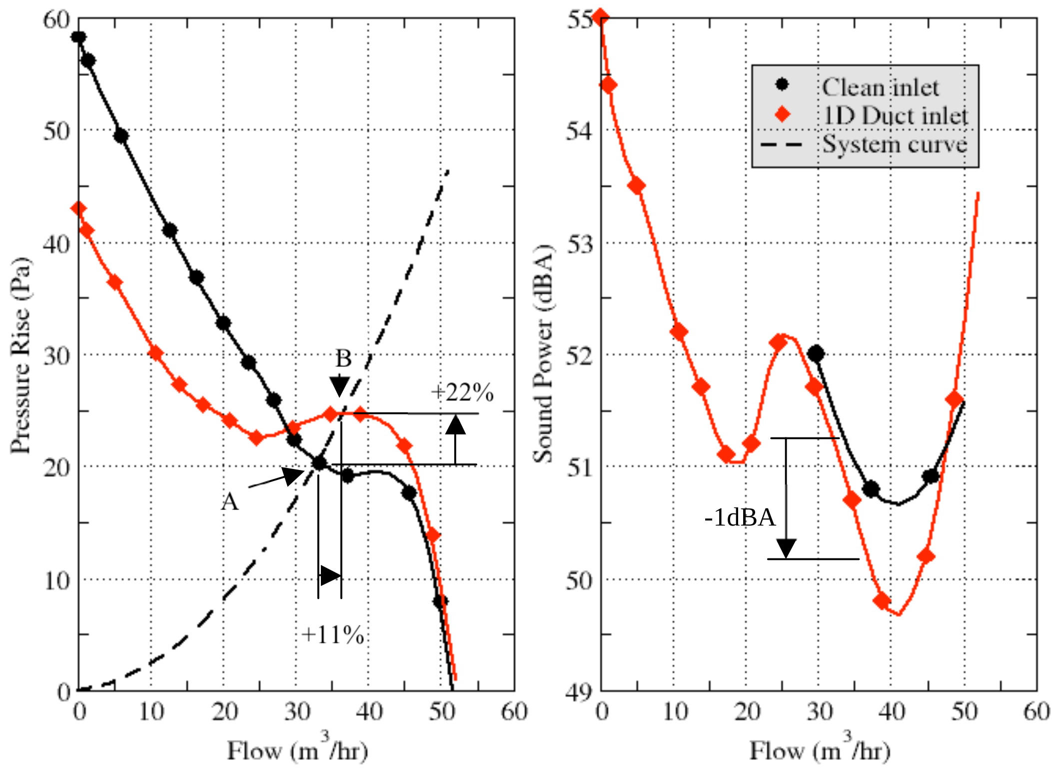

Figure 4: Aerodynamic performance and overall sound power measurements for the cooling fan with a clean inlet and also for the 1D inlet duct installed. A notional system resistance curve is also shown.

Further throttling puts the fan into an unstable region where the pressure rise is increasing to its cutoff value, but the flow in the fan is very turbulent. The fan broadband noise increases noticeably as the fan stalls. For this fan the change from tone to broadband is a good indicator of the stability boundary. The useful operating range of the fan is limited to 40 – 50 m^3/hr.

The addition of an inlet duct increases the maximum pressure rise for the fan in the stable operating region and moves the stall point to a lower flow rate. Fan static pressure rise is plotted as (fan plenum pressure – fan inlet pressure) where inlet pressure is below atmosphere due to the acceleration of the flow in the duct. The design of a short efficient inlet would eliminate this pressure drop. The inlet pressure was expected to remain below atmospheric for all flow rates above cutoff. However at flow rates less than 21 m^3/hr the inlet pressure increased to above atmospheric. The explanation for this anomalous behavior is the presence of swirling flow at the inlet which would cause a radial pressure gradient from the wall. Probing with a tuft on a knitting needle confirmed the presence of swirling flow coming out of the fan inlet. Fan pressure rise for flow rates less than 30 m^3/hr is computed using Bernoulli's equation to estimate the inlet pressure as if the flow was uniform.

A notional system resistance curve is shown on the fan operating characteristic plot. With no inlet the fan would operate at point A with the fan entering the unstable operating region. The fan is undersized for the pressure rise need of the system. The addition of an efficient fan inlet could move the system operating point to B. This would yield an 11% increase in flow rate and a 22% increase in pressure rise. The system would also achieve a 1dBA reduction in overall sound power. The fan is already struggling aerodynamically at operating point A and this would not be a desirable point for long term operation. The addition of an inlet is a simple first step in improving the fan performance and additional changes to the fan installation/geometry would yield more improvements in aerodynamic and acoustic performance.

To more precisely determine what is limiting the fan performance, detailed flow field measurements were acquired at the free delivery operating condition (50 m^3/hr) and a mild stall condition (30 m^3/hr).

5 DETAILED FLOW FIELD MEASUREMENTS

PIV and HW data for this report were acquired at locations shown schematically in Figure 5. PIV measurements characterize the inlet flow uniformity at both free delivery and mild stall conditions. Hotwire measurements of the rotor exit flow show the tip clearance flow and blade wake character for the free delivery condition.

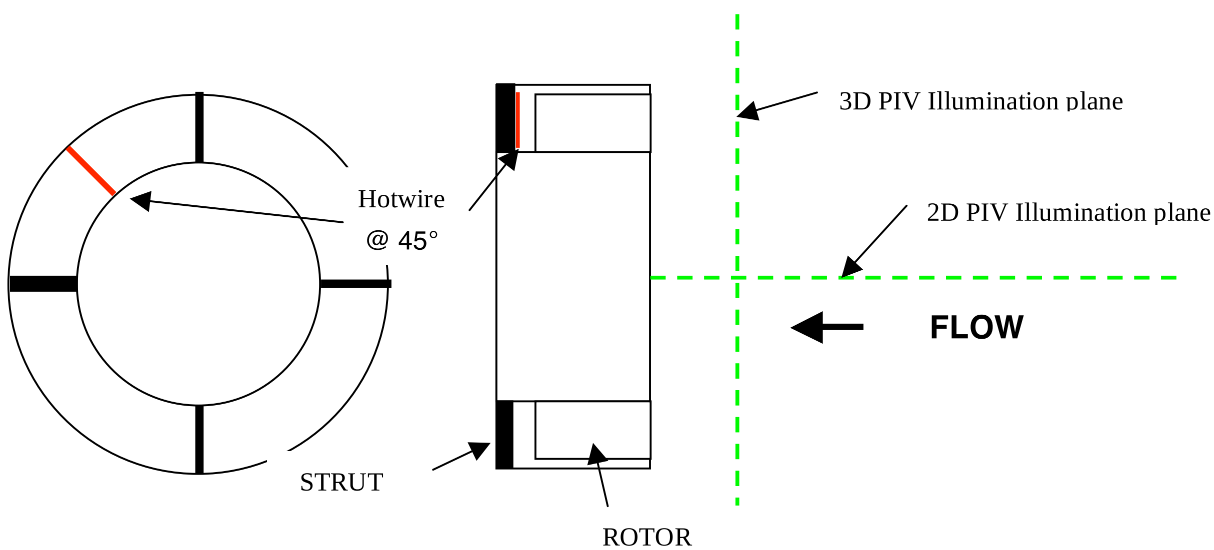

Figure 5: Rear view and cross section of fan (top view) showing PIV and hotwire measurement locations.

As shown earlier, the fan inlet frame is square with regions where the tip clearance is nominal and regions where the tip is uncovered. The influence of this non-axisymmetric inlet results in a circumferentially non-uniform inlet flow as shown in the PIV measurements of

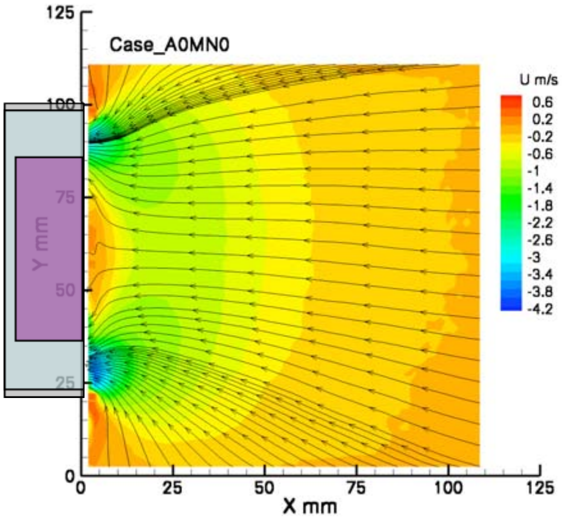

Figure 6a: Meridional view of fan inlet flow at free delivery. (U is axial velocity) 2D PIV

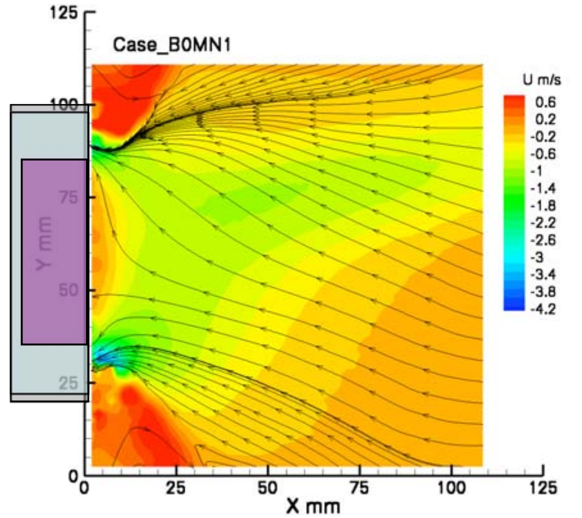

Figure 6b: Meridional view of fan inlet flow at mild stall. (U is axial velocity) 2D PIV

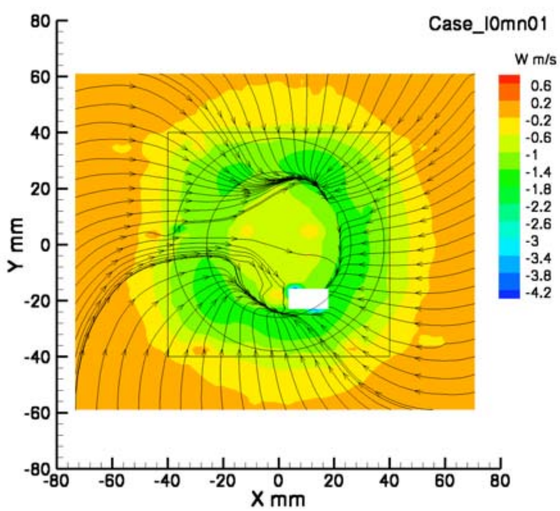

Figure 6c: Fan inlet flow at a plane 12.5mm from fan face, free delivery. (W is axial velocity) 3D PIV

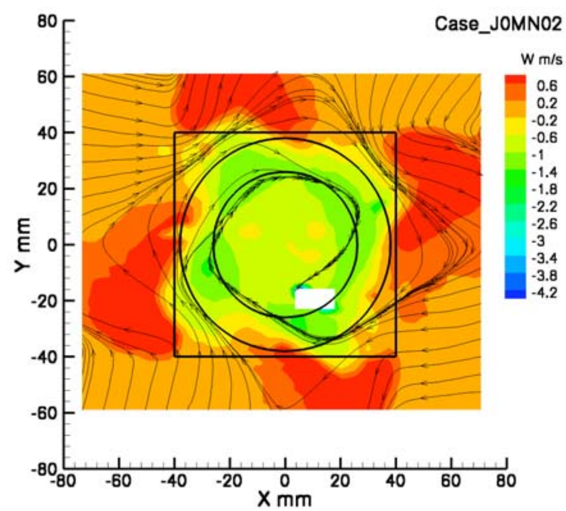

Figure 6d: Fan inlet flow at a plane 12.5mm from fan face, mild stall. (W is axial velocity) 3D PIV

Figure 6(c) for the free delivery condition. The view is forward looking aft with the desired flow direction being into the page (-W direction in this coordinate system). Streamlines are included on the plots to help show flow direction. The white rectangles in Figure 6c and 6d are blanking erroneous data which were caused by a reflection from the hub surface. The inlet flow shows a 'squared off' character instead of being perfectly circular. The rotor will perceive this non-uniformity as a periodic flow distortion similar to an inlet strut. Previous work on a fan with a similar inlet shape demonstrated that replacing the square inlet with a round bellmouth reduced the overall sound power by 2.5dB[6].

The meridional view, Figure 6(a), shows that the flow does not negotiate the sharp inlet edge to enter the tip region of the fan. This separated or 'dead air' region blocks the outer portion of the annulus (about 10% of the total flow area) from doing useful work. The reduction in useful flow area for the fan is even more evident in the exhaust flow field HW measurements, Figure 7. High turbulence intensity is indicative of inefficient flow and is seen in the blade wake, tip clearance flow and hub flow. The rotor wake is wide and its turbulence intensity is very high, greater than 20%, indicating that the blade shape and/or incidence angle is not optimum. The tip clearance flow extends from the casing to at least 60% span in some regions and is a large blockage of useful flow area. The uncovered tip region in the inlet could accentuate the tip clearance flow at this measurement location. There is also evidence of a thick hub boundary layer. The fan is lightly loaded at the free delivery condition and thus the rotor wake and boundary layers should be thin and well behaved. The poor inlet geometry and large tip clearance height are clearly detrimental to the fan performance.

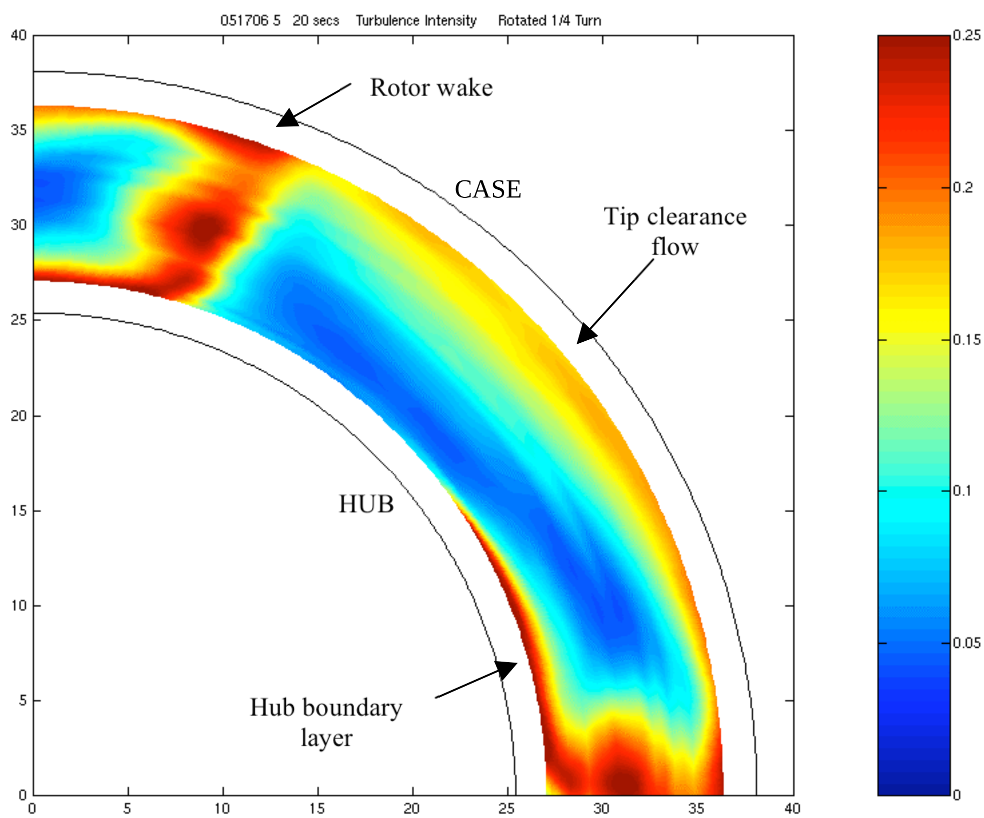

Figure 7: Hotwire measurements of turbulence intensity at the rotor exit. (0.1 = 10%)

At the mild stall operating condition the inflow to the fan gets more complex and sub-optimal for cooling purposes. The meridional view, Figure 6(b) shows flow coming out of the fan inlet at the outer blade span. This flow also has a swirl velocity in addition to the upstream going axial velocity, as shown by the streamtraces in Figure 6(d). The presence of swirling flow in front of the fan explains the anomalous above atmosphere wall static pressure readings observed during the performance testing as explained earlier. The four lobed character of the reverse flow is due to the four uncovered tip regions in the fan inlet where the reverse flow preferentially ‘leaks’. For this condition, only a portion of the fan inlet flow is exhausted possibly leading to a situation where hot air is recirculating inside the enclosure that the fan is meant to cool.

The asymmetry of the inlet flow in Figure 6(b) is due to the ingestion of a vortex similar to a ground vortex that sometimes forms when jet engines are stationary and running near the ground. It is not clear if the presence of the vortex is due to proximity of the aquarium walls in the PIV experimental setup or is a salient characteristic of the stalled fan. A coherent structure, like a vortex in the fan inlet flow, will be an additional noise source.

6 DISCUSSION

Applications of cooling fans are requiring a higher pressure rise for a given flowrate due to the packaging density of electronic components. Due to acoustic requirements, simply increasing the tip speed to meet the pressure rise requirement is not acceptable. Better installation of existing fans and, in the future, better aerodynamic design of the fan itself will be needed to meet the performance requirements within acoustic limits. Low-speed cooling fans are still far from their ultimate performance potential.

For the fan studied here, the square edged inlet and large tip clearance resulted in significant flow blockage in the fan blade passage. Adding the duct inlet guides the flow into the fan face so that the streamlines are axial and the rotor has a better incidence angle at the leading edge. Thus there is less inlet blockage at the casing, the rotor blade tip is able to work more effectively, the fan generates a higher pressure rise, and the stable operating range is extended. The acoustic benefit of the duct was small but a well designed inlet should increase this benefit.

The mild stall condition shows a surprisingly complex inhomogeneous flow field with reverse flow at the fan inlet. This is not an acceptable operating point for the fan as originally installed. An underestimate of the system resistance during design and a poor fan installation could cause this condition. Fortunately, with a better installation, the fan operating point can moved back into the stable operating region.

7 CONCLUSIONS

Analysis of a commercial cooling fan showed the large tip clearance height, non-axisymetric inlet geometry and lack of an inlet bell mouth significantly limit the performance of the fan. The addition of a simple 1D duct inlet increased the stable operating range of the fan and allowed a higher pressure rise. For a notional system curve, the flow increased 11% and the pressure rise by 22% with a 1dBA reduction in overall sound power. The better performance is due to a more optimum inlet condition to the fan.

Future work should include the design of a short, efficient fan inlet and a re-design of the rotor including an improved hub geometry and tighter tip clearance[14].

8 ACKNOWLEDGEMENTS

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