Improved Energy Efficiency for Data Center Cooling Fans

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ABSTRACT

Data centers worldwide use about 30 billion watts of electricity per year, with the US making up one-quarter to one-third of that load (Glanz 2012).

Rack servers in data centers produce excess heat as a byproduct of computation, and require internal cooling fans to cool Central Processing Units (CPUs) and other components. These fans use significant energy, which is parasitic in that it does not go toward any actual computing task.

PAX Scientific, Inc. (PAX) has developed the Streamlining Principle, a technology based on principles of fluid movement in biological systems. When applied to fan geometries, the Streamlining Principle creates fans that are significantly more energy efficient than fans designed by conventional means, and quieter, since noise reflects wasted energy.

PAX technology was demonstrated and tested by Cisco Systems in San Jose, California, where PAX fans were compared to the fans in Cisco's Nexus 7000 Series server switch. The demonstration was highly successful, with a power drop by PAX fans of 35%-45% for matched cooling. This greatly exceeded the original goal of 15%. PAX fans can be manufactured with the similar cost and processes as current fans and have potential applicability to data centers worldwide.

This report includes project specifications, information on the development of the fan design, and results of experimental testing. This project was partially funded by a grant from the California Energy Commission's research and development program.

Project Overview

PAX Scientific, Inc. (PAX) is a California-based research and licensing company that specializes in innovative solutions for fluid-related industrial problems using biomimicry. Biomimicry is an emerging field of engineering design that seeks to emulate the energy-efficient systems that have evolved in the natural world. After recognizing that spiraling flows could be found in all forms of nature, naturalist and PAX CEO Jay Harman used that observation to identify a set of geometries that nature applies ubiquitously to reduce friction and drag in flow structures, plants, and animals. Harman patented these geometries as they apply to many product areas in a range of industries including fans, blowers, mixers, thermal products, propellers, pumps, and turbines. PAX geometries bring a variety of benefits to products, including:

- Friction and drag reduction in fluid handling
- Reduction in fluid noise/cavitations
- Improved energy efficiency in rotating blade and propulsion mechanisms
- Improved structural integrity in surface profiles
- Reduced environmental impact

Application

Computer servers, and their associated cooling and auxiliary infrastructure, account for roughly 1.7-2.2% of the total electricity demand in the United States (Koomey 2011). Large server farms are intense users of electricity and they are sited based on electricity cost and availability.

Servers, in addition to being located in air-conditioned rooms, primarily cool themselves by means of several small fans mounted in the chassis of the device. These pull air across the circuit boards and other vital components. These fans are typically 40-150mm in size and use up to 200 watts of power per fan. The number of fans per system varies directly with the computing power; 12 to 24 fans per server chassis are not uncommon.

Project Goal

The goal of this project was to demonstrate a 15% reduction in the energy consumption of server fans by retrofitting a commercially-available server with PAX's biomimetic fans. In order to achieve this, PAX:

- Partnered with Cisco Systems, Inc. and Jabil Circuit. Cisco is a worldwide leader in IT hardware and software and Jabil is a supply chain management and manufacturing partner that currently provides many components, including fans, to Cisco.
- Iterated in-house design tools (analytic and computational fluid dynamics) to prepare them for server-specific fan designs.
- Designed a fan optimized for the selected server and completed baseline tests.
- Fabricated pre-production samples.
- Installed PAX fans in a server and monitored power usage under typical operating conditions to compare with current best-in-class server fans.

Project Specifications

Server Selection

The server fan chosen to target was a mid-range 120x120x38mm fan. This type of fan is a typical server chassis and is very power intensive. Cisco currently uses this fan in its line of Nexus server switches: a 9-slot chassis and an 18-slot chassis. The 18-slot version uses 24 of the 120x120x38mm fans and the 9-slot version, referred to as "Boxster," uses 12 of these fans. Both Cisco servers sell approximately 1,000 - 2,000 units/month, equivalent to 500,000 - 800,000 of the 120mm fans per year for the 5-7 year lifetime of each server. Each fan uses about 1.1Amps (at 48Volts), which can account for as much as 25% of the total power usage to the server.

The Boxster is a 9-slot server chassis of approximate dimensions 18"x24"x24" shown below in Figure 1. The total power usage in the chassis is 6KW at maximum. The cooling fans are installed into a tray that slides into the back of the chassis for assembly. The fan tray has 12-120x38mm fans and 6-80x38mm fans. One side of the chassis is perforated with hexagonal 2mm holes where the air enters. Air is pulled across the server nodes (perpendicular to the rack) by the fans that are flush with the outlet wall of the chassis (also with perforated hexagonal holes).

This server typically ships with a combination of Delta or Nidec fans. In order to isolate the 120x38mm fan performance, the 80x38mm fans were not powered during in-unit testing.

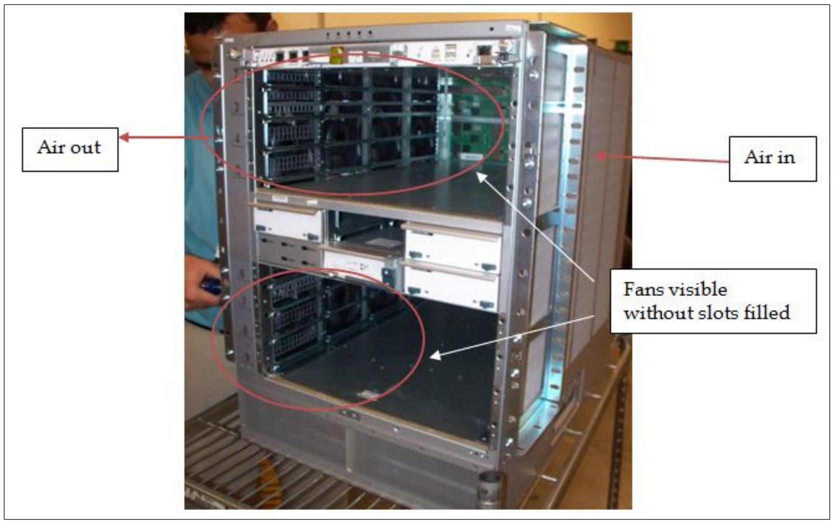


Figure 1: Boxster front view with fans visible

Competitor Fan

The primary fan for comparison was the Nidec Model T12E50BS2M7-07, shown below in Figure 4. The outer casing is 120mm x 120mm x 38mm. The fan has an imbedded 50V motor, and the speed is controlled using pulse-width-modulation software. The 120mm x 120mm x 38mm Delta Model AFC1248DE was also compared. These fans currently ship in the majority of Boxster units and were identified by Cisco as being "best-in class." The baseline data for the fans are shown below in Figures 2 and 3.

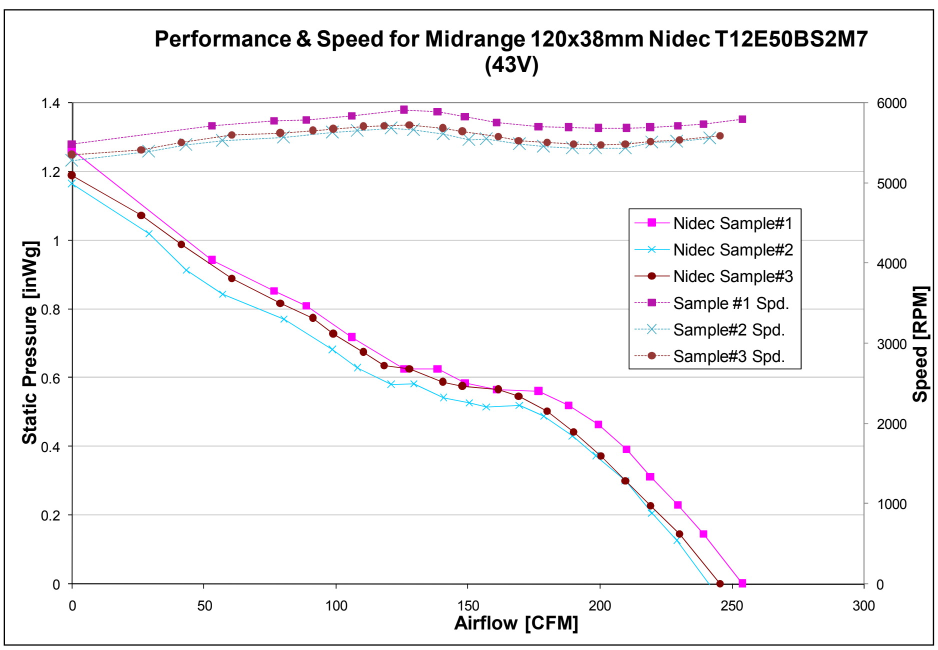


Figure 2: Airflow & Speed Baseline Data

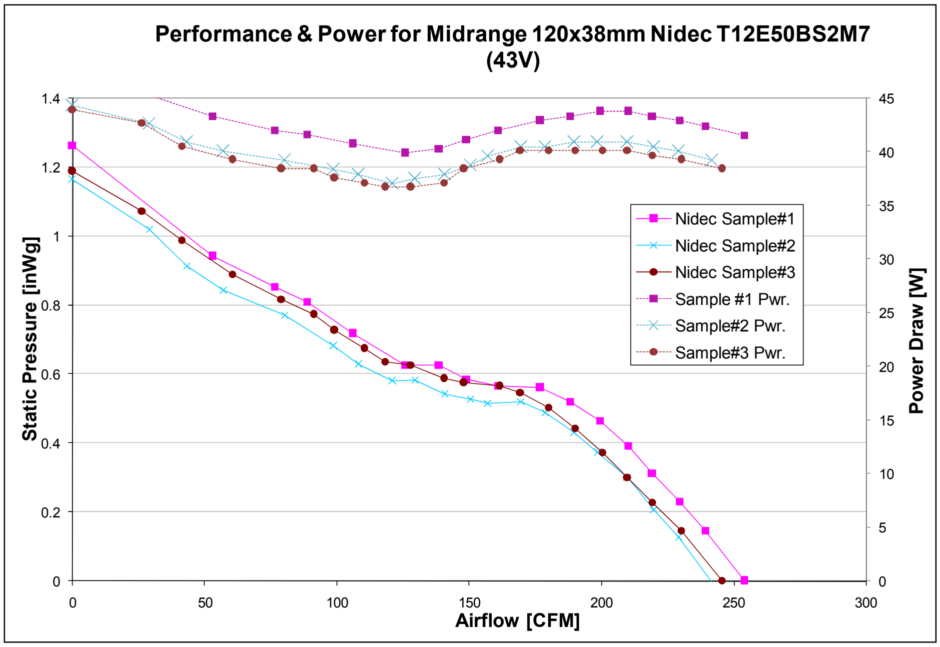


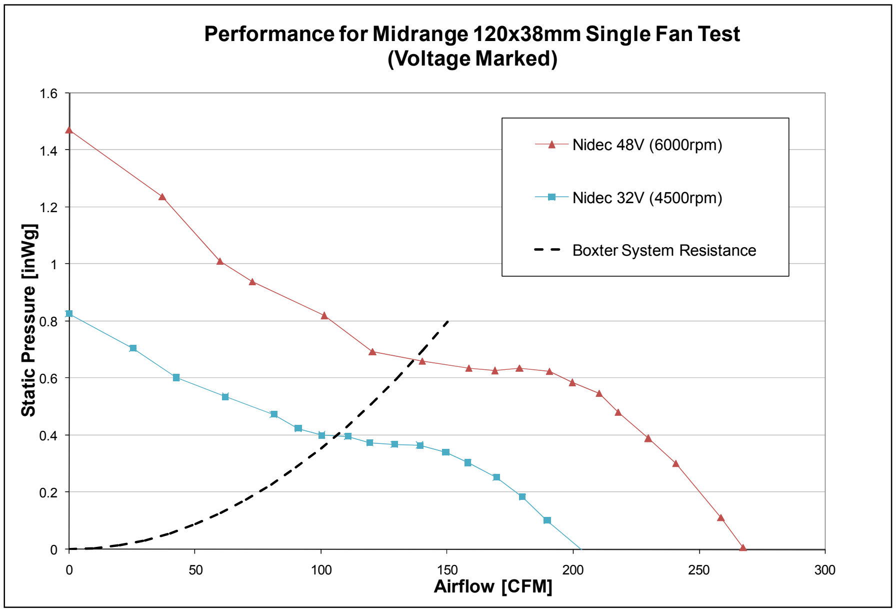
Figure 3: Power Baseline Data

Figure 4: Upstream and Downstream View of Competitor Fan

Test Procedure with Correlation

To demonstrate the PAX fan power reduction in a repeatible, real-world environment, a test procedure in accordance with AMCA 210 and international standards was developed in collaboration with Cisco. Initial fan-alone airflow and noise tests were completed at the PAX Fan Laboratory in San Rafael, California. The tests with fans installed in the server were completed at the Cisco Test Laboratories in San Jose, California. A high level of correlation was found between the two facilities.

Shown below in Figures 5 and 6 are the single fan data for the midrange 120x38mm fan that Cisco uses in the Boxster chassis. Cisco also provided PAX with an operating point that represents the system resistance imposed on the fan by the fully loaded chassis. Using the performance curves and the system resistance data, PAX can approximate how the fan will perform when installed in the Boxster chassis. The curves below show the midrange Nidec fan performance in a single fan test at two different speeds.



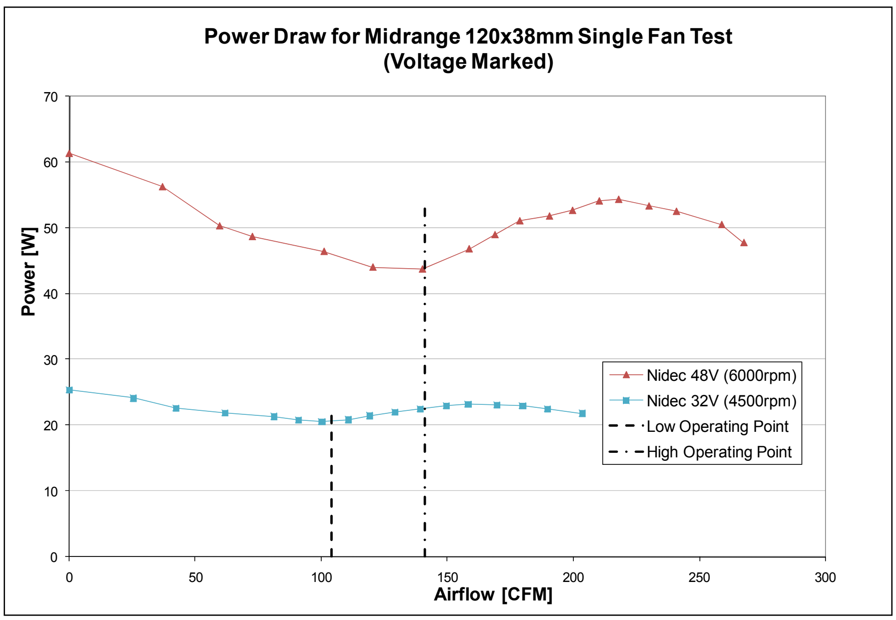


Figure 5 & 6: Baseline Single Fan Airflow & Power Data – PAX Lab

Following testing at the PAX facility, twelve Nidec fans were brought to the Cisco test facility for testing. Using the operating point predictions for airflow from the PAX tests, approximated values were compared to the actual values tested in the chassis at Cisco. PAX approximated the output at 138CFM and 106CFM at the 100% and 60% duty cycle operating points, respectively. Actual airflow values per fan were 141CFM and 104CFM, respectively. These match very closely and power predictions also correlated.

PAX Effort: CFD Overview

PAX engineers use CFD simulations both as a performance predictor and, more importantly, as a flow visualization tool. By studying the pressure contours and velocity contours along the blade surfaces and in the downstream vortex, PAX can reduce areas of unwanted turbulence and improve performance. Before PAX used CFD simulations for its fan design process, it investigated various geometric, grid, and physical modeling assumptions to establish a method with good experimental correlation.

PAX's first task was to find the proper geometric control volume for defining the CFD model. It was determined that modeling the actual 1000 CFM flowmeter tunnel in the PAX Laboratory would give the best correlation. This flow meter has two basic sections. The first section is where the fan and its shroud/housing is mounted flush to the front plexiglas surface. The next section allows the air to either exit to ambient, if the rear plexiglas surface is removed, or exit to a large flexible hose that is connected to a blower, which can be operated in tandem with a pivoting baffle over the flexible hose exit to control flow rate through the flowmeter tunnel. Figure 7 below shows this simplified flowmeter tunnel geometry, with an information technology (IT) fan attached to the right and an 3-inch exit nozzle on the left showing typical air particle paths.

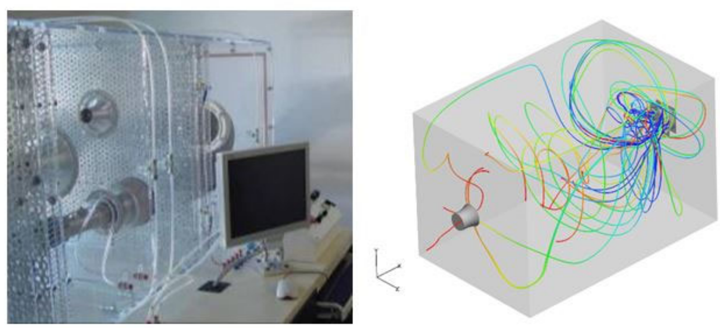


Figure 7: 1000cfm Flowmeter Tunnel and Simplified Flowmeter Tunnel

In order to finalize the computational control volume geometry, one must define the means by which the flow rate and pressure drop (operating point) will be regulated multiple times in order to define a fan curve. A 'novel' approach is to model a large portion of the surrounding test area's high bay and drive the flow only by the fan and its rotation. With this approach, different operating points can be achieved by changing the exit nozzle diameter and geometric shape. In this manner, no inlet or outlet boundary conditions need to be specified.

For the second task, PAX carried out a mesh sensitivity study. The goal in crafting a proper specification of isotropic mesh sizes (and viscous layer sizes) is to explore how mesh size variation effects the primary fan performance measure for a given simulation (pressure drop, flow rate and torque of the fan). In this way, a serious attempt to make the predicted results independent of the grid was executed.

All simulations were carried out using PAX's High Performance Cluster (HPC). The cluster has a head node and 16 compute nodes for a total of 192 cores that include Infiniband interconnects to improve inter-processor communication and decrease memory latency. Two different commercial CFD packages were used: AcuSolve from Altair Engineering and STAR_CCM+ from CD_ADAPCO. Simulations were completed using both steady and unsteady physical modeling, to help remove any potential error in the computed results due to not properly resolving temporal features of the flow.

Comparing CFD and experimental curves indicated that the CFD results for the commercial cooling fan were good and those of the IT fan were fair. Both sets of fan curves showed that steady MRF simulations were not as accurate, so one should run unsteady simulations if possible. The fact that AcuSolve and STAR_CCM+ both produced similar unsteady results confirmed that simulations with basically the same 'ingredients' gave the same results.

For the remainder of the project, experimental results were used to accurately characterize the overall performance of each fan design. However, the CFD simulation was still useful. In particular, its added value was to provide fine grain flow characteristics for a given baseline fan operating point and another improved fan design variant nominated by PAX's Fan Parameter Optimizer (see next section) as a means to understand WHY certain parameter changes improve or reduce fan performance. Visualization of the three-dimensional fan flow regime (pressure, velocity and turbulence) is a real benefit.

PAX Fan Parameter Optimizer

The first challenge in applying the PAX optimization process to cooling fans was to develop an efficient optimization objective function specific to a cooling fan. The mathematical formulation of the optimization problem is given by

$$\hat{X}(OC) = \underset{X}{\operatorname{argmin}}\, f(X, OC)$$

where f is the cost function, X is the set of geometrical parameters, OC is the set of operating conditions (such as flow, pressure, power, etc.) and $\hat{X}$ is the optimum set of parameters that minimize the cost function.

Fan performance is characterized by fan curves consisting of the pressure and power as a function of the air flow rate supplied by the fan. A certain fan will generally perform better under a specific range of operating conditions. Therefore, the selection of an optimal fan depends directly on the operating conditions.

In that context, it was necessary to formulate an objective function that incorporates the operating conditions, such as airflow rate, pressure and/or power, and uses the fan curves as the input information. The methodology implemented in the PAX design toolbox is depicted in Figure 8 below.

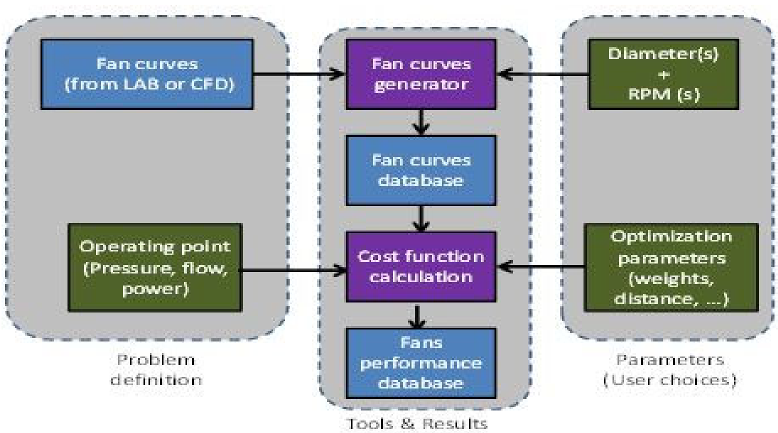


Figure 8: Implementation of an Objective Function Applied to Cooling Fans

The second challenge was to select and quantify the parameters used for the fan design tool. PAX selected 25 initial parameters, some of which are shown in Figure 9 below.

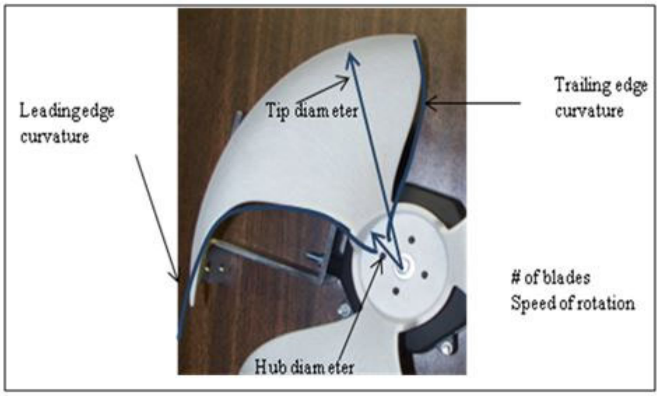


Figure 9: Fan Top View with Parameters Labeled

The third step was to generate fan curves at various diameters and motor speeds using the existing database and scaling laws. This created a master database of fan curves that can be used to compute an objective function.

The next step was to select an operating point along the fan curve (pressure and flow) for which the optimization will be performed. Then, each fan curve is analyzed using the following cost function equation,

$$f(X, OC) = \begin{cases} Power, & if \;\; OC \in FC(X) \\ & \infty, otherwise \end{cases},$$

where FC(X) represents the fan curve for a specific set of parameter X.

Using this parameterized fan model, methodology, and process, PAX developed a functioning Fan Parameter Optimizer. Using MATLAB coding and visualization software, it was used in the development of the high efficiency PAX server fan, in combination with CFD and prototype testing.

PAX Fan Design Process

In order to utilize the PAX fan parameter optimizer described in the previous section, PAX needed a large database of fan samples that were diverse in their parameter combinations to provide insight over the largest range. One of the methods used to create a random sampling of parameter combinations was the Orthogonal Method. Once these designs are created in computer aided design (CAD) software, the fan performance curves must be generated so that the optimizer can evaluate a cost function correlating the parameters to how well the fan performs. Each of the fan designs was generated in CAD, and a rapid prototype was generated using the outside vendor. The fan was then tested in-house using PAX's flowmeter and dynamometer.

Once the parameter combinations were established, the CAD files generated and prototyped, and all the testing completed, the PAX parameter optimizer helped PAX analyze their results. With each design iteration, PAX studied the parameter values of the most promising designs, and narrowed its focus to a subset of geometric factors that led to further improvements in design.

PAX developed a parameter set and fan design, shown below in Figure 10, that it felt confident would meet the project goal of 15% power reduction in the Boxster chassis. Figures 11 and 12 below show data generated using prototype materials and run on PAX's dynamometer. Compared with the Nidec fan, the PAX design predicts a much higher output at the operating point while using less power. When run slower to just match the cooling capability of the competitor Nidec fan, this initial estimate predicts that the PAX V1 fan design will produce about a 35% drop in power usage compared to the best-in-class Nidec fan currently shipping in the unit.

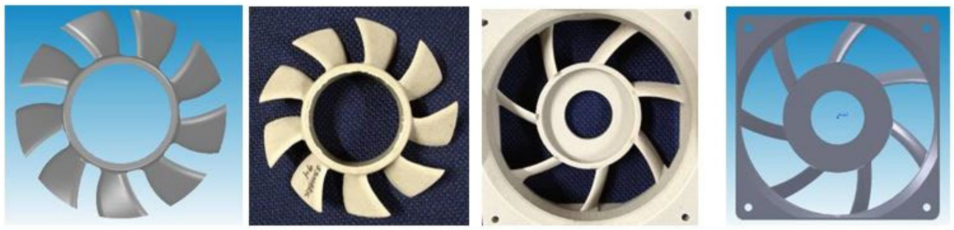


Figure 10: PAX V1 Fan Blade & Frame in CAD & Prototype

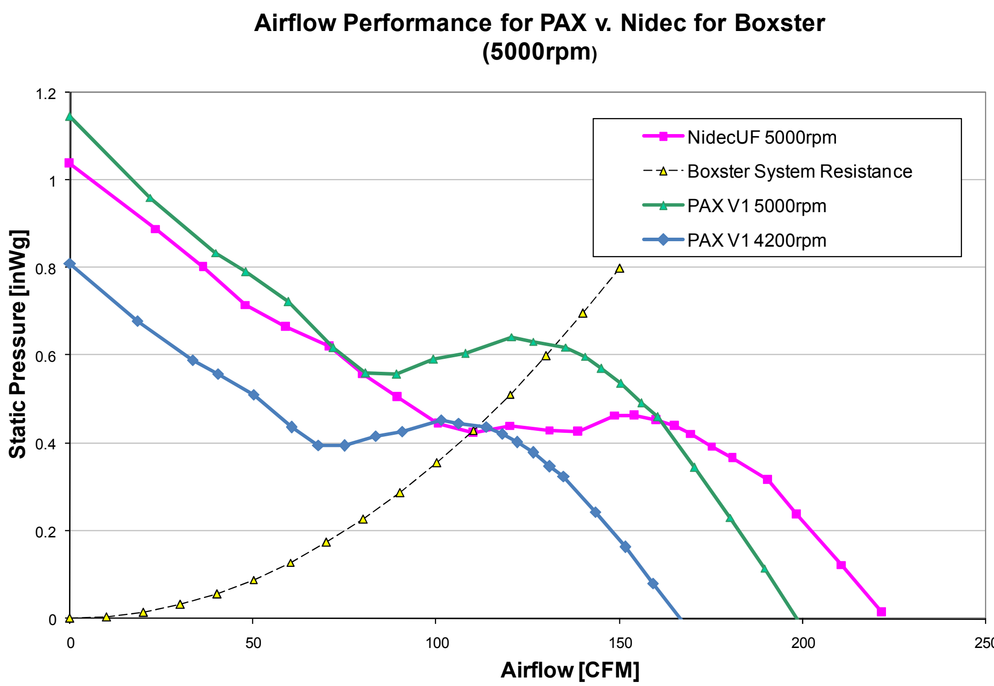


Figure 11: Airflow/Pressure Data for Final PAX V1 Design

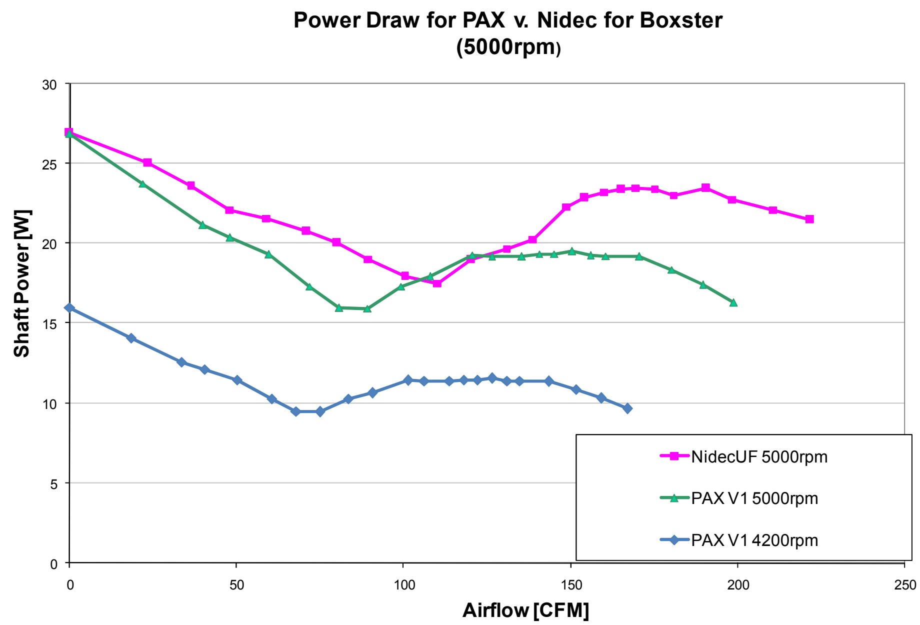


Figure 12: Airflow/Pressure & Power Data for Final PAX V1 Design

PAX Pre-production Prototypes

Following the design phase, PAX created a more manufacturing-ready version of the PAX prototype on a Nidec motor for testing in the Boxster chassis at Cisco. The samples to be tested by Cisco needed to have all of the same outer and mounting dimensions as the conventional fans. More importantly, they needed to interface with the server's existing internal controller and adjust in speed in an analogous manner to the conventional fans. It was determined that the best way to accomplish this was to use the motor from a Nidec model number T12E50BS2M7-07 fan currently being used in the server, and assemble it to the PAX fan and housing design.

A sample set of the Nidec motors was obtained, isolated from their initial fans and frames, and verified for performance. These motors were then assembled into rapid prototypes of the PAX fan and frame design created from the optimized parameters. Because of the high rotational speeds at which these samples would be tested, it was necessary to have the functional samples balanced. The assembled samples were sent to an outside vendor that measured the imbalance of each sample while powering the fan, and added small epoxy masses in the inner hub in order to reduce the imbalance. Performance of the samples was verified at the PAX lab and corresponded well to the initial dynamometer results shown in the prior section.

Comparative Power Consumption Monitoring

All of the following test results were generated at the Cisco Test Facility in San Jose, California by Cisco engineers with the assistance of PAX engineers. The procedure followed was in accordance with AMCA 210 standards. The tests measured the performance from a 12-sample installation of three different 120x38mm fans:

1. The PAX V1 Pre-Production Samples (as shown in Figure 13)
2. The Delta Electronics Model #AFC1248DE (currently ships in unit)
3. The Nidec Model #T12E50BS2M7-07 (currently ships in unit)

Figure 13: Upstream & Downstream Views of PAX Pre-Production Samples

Boxster Chassis

Figure 14 below shows the 12-fan airflow output (proportional to cooling) measured from the Boxster chassis across the x-axis, and the power draw necessary to create that amount of airflow along the y-axis for each fan set. The PAX fans are shown in blue, the Nidec fans are in red, and the Delta fans are in green. The lower end of the curves represent the lowest duty cycle tested of 20%. The upper right-hand side of the curve represents the high duty cycle of 100%. In order to examine equal cooling, one can draw a vertical line through the graph showing equal airflow output, and then look to the left axis to see how much power is used by each fan set. Throughout the entire duty cycle, the PAX fans use significantly less power than both the Nidec and Delta fans for equal cooling.

Two example points are highlighted in Figure 14. At a low duty cycle, with about 850CFM of cooling, the PAX prototypes use 41% less power than the Nidec fans and 46% less power than the Delta fans. At the high duty cycle with about 1700CFM of cooling, the PAX prototypes use 37% less power than the Nidec fans and 46% less power than the Delta fans.

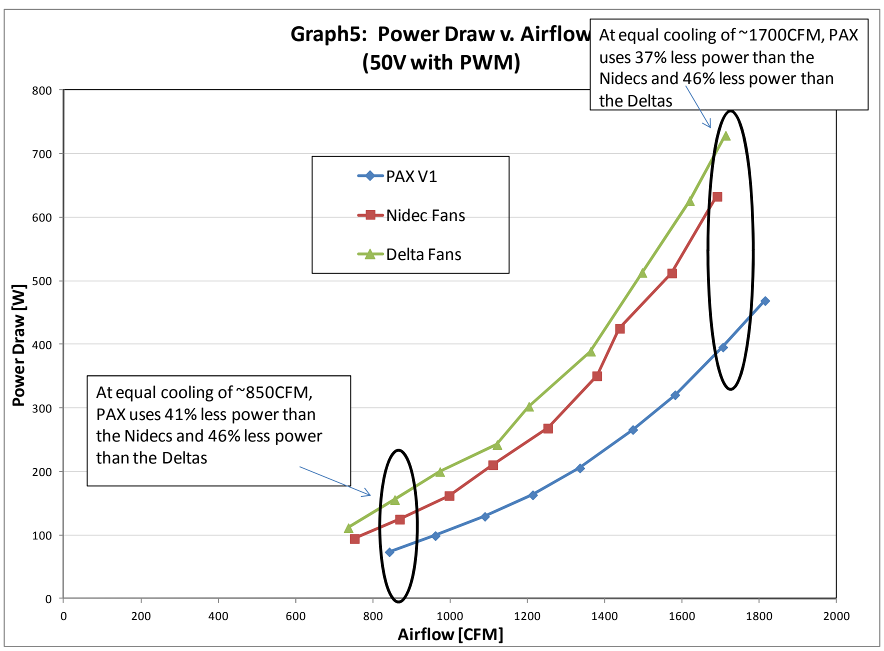


Figure 14: Airflow/Power Comparison for PAX & Competitors Installed in Server

Figure 15 shows the same airflow output but graphs it against the total sound power level generated by each fan set in the Boxster chassis. The same low and high duty cycle comparison examples are highlighted, and this graph can be analyzed in a similar manner, by drawing a vertical line for equal cooling and comparing each fan type's sound power level. At the lower duty cycle point, the PAX prototypes are 2.8dB quieter than both the Nidec and Delta fans for equal cooling. At the higher duty cycle point, the PAX prototypes are about 1dB quieter than the Nidec and Delta fans for equal cooling. Although this is a small drop in noise, the PAX prototypes are never louder than the competitor fans throughout the duty cycle, while greatly reducing the power consumption.

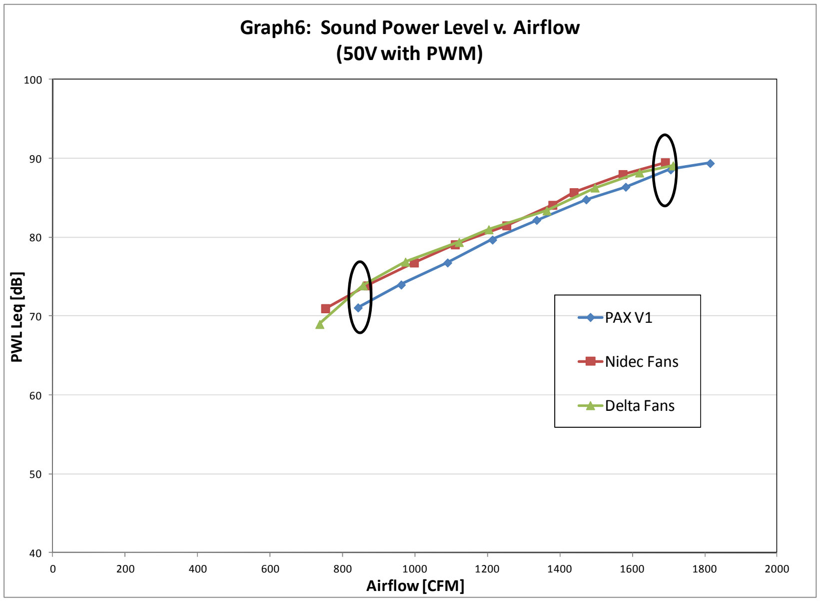


Figure 15: Airflow/Sound Comparison for PAX & Competitors Installed in Server

Conclusion

With help provided by a grant from the California Energy Commission, PAX had a goal of demonstrating at least a 15% drop in power draw for matched output in a server, as tested by an outside party.

PAX greatly surpassed this goal and designed a fan that produced a 35-45% power drop in the selected server chassis compared to the current best-in-class fans, as specified and tested by Cisco and Jabil. The PAX design offered an additional noise benefit as well.

The twelve fans targeted used about 700W of power at full duty cycle. The PAX fans use less than 400W. This power savings only represents one 9-slot chassis. A typical data farm would have hundreds or thousands of these chassis. PAX fans are the same cost to manufacture and fit into existing architecture. Switching to PAX fans in servers can have a significant reduction in wasted energy, greatly reducing operational cost and greenhouse gas emissions.

References

Glanz, J. "Power, Pollution and the Internet", *New York Times*, September 23, 2012: A1.

Koomey, J. 2011. *Growth in Data Center Electricity Use 2005 to 2010*. Oakland, CA: Analytics Press.