Abstract

The continuous rise in power dissipation levels combined with a reduced cabinet footprint is the norm in the electronics industry - a trend that is likely to continue. While advanced cooling systems such as spray cooling, jet impingement, and liquid cooling may provide solutions for the removal of high local heat fluxes, forced air cooling remains to be the most practical and the most widely used thermal management solution in practice today, largely because it is reliable and well understood. However, larger cooling demands require higher airflow rates which in turn may require novel fan designs and/or a better understanding of fan-system interaction. Increased airflow rates also come with a noise penalty. By taking a detailed look at the fan design, fan-system interaction, and fan acoustics emissions, forced air cooling can live up to its highest potential.

Current Challenges

Air Flow

Traditionally, the fan has been modeled as a black box or as a lumped parameter within the overall system. Its effect on the system is applied via the fan curve (static pressure, Pa or mm H₂O vs. flow rate, CFM or m³/s), see Figure 1. The fan curve is typically obtained through experiments that are done according to the Air Movement and Control Association (AMCA) standards; an example of the experimental set up is shown in Figure 2. To obtain the fan curve, the rpm is fixed while the backpressure of the fan is varied by changing the size of the exit opening.

From a first glance of Figure 2, it is evident that the flow configuration the fan experiences during the test mode is different from that it is going to experience when it is installed in the system. For example, there are no obstructions upstream of the fan and the flow downstream of the fan is straightened. Changing either upstream or downstream flow configurations in the installed conditions will likely have an effect on the actual fan performance because the fan blades will be
exposed to different incoming flow. Also, the downstream system blockage will influence the local flow through the fan. Changing the angle of attack of the flow around an airfoil certainly changes the amount of lift or drag (or pressure rise in that case) it will deliver. Obtaining a fan performance curve under installed conditions is not only impractical but it would have to be repeated every time a new system layout is tested.

The solution to this challenge would be to include the details of the fan blades in the overall system model including the number of blades, blade angles, hub diameter, blade size (span, chord etc.) and rpm. Doing so ensures realistic fan system interactions since it does not rely on a measured fan curve that cannot represent all possible operating scenarios for the fan in all possible system configurations. The details of the fan blades may be incorporated in an overall system model either mathematically or by physically representing the actual blade geometry as part of the system model.

Mathematical representation of the blades is often called virtual blade modeling (VBM)\(^3\),\(^4\). It differs from the lumped analysis because it uses just the fan curve by adjusting not only the pressure rise as a function of the flow rate, but also the local three-dimensional flow and pressure according to the incident flow angles, blade type, geometry, dimensions and rpm. Another way of looking at the differences between the VBM and the typical lumped fan analysis model is that instead of having a mathematical model representing the entire fan performance, the VBM is actually a mathematical model representing the performance of the individual blade. The advantages of this approach are higher fidelity in capturing the effects the blade geometry has on the flow as well as better representation of the effects of local flow incidents.

On the other hand, a true physical representation of the blade geometry within the system would offer an even higher level of accuracy. Including the fan details using a multiple reference frame (MRF) or frozen rotor approach\(^5\), see Figure 3, to model the actual blade rotation in the system would eliminate the need for a fan performance curve with all its uncertainties in measurements and data interpretation. The MRF approach, although computationally more expensive than the previously discussed models, would deliver the most realistic fan system interactions. This should help in optimizing the fan design with respect to a particular system at the design stage, see Figure 4. Having a more accurate measure of the amount of air delivered by the fan would lead to a better estimate of the cooling performance and a better prediction of the junction temperature. Also, since local variation of air flow downstream of the fan is captured, the effects of non-uniform flow on the fins cooling can be readily estimated. The resulting undesirable non-uniform temperature variation can be predicted and design changes can be made to either work around this problem or reduce it.
Fan Noise
Acoustics emissions from fans are the main noise source in forced convection air cooled systems\(^2,6\). There are several standards aimed at characterizing the acoustical performance of complete electronics systems as well as of air moving devices (AMD) used in the electronics industry. For example\(^7\), ISO 7779 standard, “Acoustics – Measurement of airborne noise emitted by computers and business equipment,” is internationally accepted for measuring noise emissions from personal computer system units, hard disks and other storage media. ISO 10302 standard, “Acoustics – Method for the measurement of noise emitted by small air-moving devices,” on the other hand is accepted for noise measurement of fans. Nevertheless, fan vendors report their acoustical data in several ways if at all. Some report the acoustic emission at free flow rate\(^8\), often in terms of sound pressure level (SPL) in decibels (dB) at one meter from the fan inlet. SPL measurements are only meaningful however when reported vs. frequency rates and the receiver location is explicitly mentioned. Another quantity that may be reported is the sound power level of the noise source which should be reported in bells (B) but in many cases is also reported in dB (1 bell = 10 dB). Because it is a measure of the source noise, it does not require a receiver location to be specified.

Bells or decibels are not physical units by themselves; they are simply logarithmic expressions of ratios as follows\(^9\):

Sound pressure level (SPL) in dB = \(20 \log_{10} \left( \frac{p}{p_{\text{ref}}} \right)\)

Where by definition the reference pressure \(p_{\text{ref}} = 20 \mu\text{Pa}\). This reference value is the minimum root-mean-square (rms) of a pressure fluctuation that a healthy human ear will be sensitive to\(^9\). This means that a value of zero dB does not mean zero sound, but rather a sound level that is equal to the reference value. Negative dB may also exist, which simply mean SPL that is less than the reference value (in theory this means no sound for us humans). Similarly, the acoustic power level is also reported in bells or dB as\(^9\):

Acoustic power level in dB = \(10 \log_{10} \left( \frac{W}{W_{\text{ref}}} \right)\)

Where the reference power \(W_{\text{ref}} = 10^{-12} \text{ Watts}\)

Because SPL and acoustic power level may be reported in dB, care must be taken when interpreting catalogue data of acoustical fan performance.

Another important point to highlight is the way our human ear responds to noise. The human ear responds differently to noise at different frequencies. This means that a certain SPL at a low frequency may “sound quieter” than the same SPL (having the same dB) at a slightly higher frequency. In fact, within the range of audible frequencies (20 Hz - 20,000 Hz)\(^10\), the human ear is most sensitive around 4000 Hz\(^11\). One theory is that this frequency is similar to the resonance frequency of our hearing system. This selective response or filtering behavior of the human ear is represented mathematically.
Increasing Air Cooling Efficiency Through Advanced Fan Modeling

through the so called ‘filters.’ The most common is the A-filter (Figure 5) which attenuates most of the low frequencies of an acoustic signal similar to the human ear. Typically, catalogue data are already filtered, however to distinguish between unfiltered and filtered values, typically “A-filtered” values are reported in dBA, or dB(A), whereas unfiltered values are reported in dB.

![Figure 5: Schematic for dBA filter](source)

Filtered SPL vs. frequency data can be used to find out whether there is audible discrete tonal noise. This is highly undesirable, difficult to eliminate and will result in discomfort for the user. This is typically a function of the fan design and is less sensitive to system layout around the fan. The other type of noise is broadband noise or white noise. This noise does not have a dominant frequency; the name ‘white noise’ is analogous to ‘white light’ which consists of a mixture of all the visible light bands. Acoustic power level may better describe this noise type.

![Graph showing human ear sensitivity vs. frequency](source)

Broadband noise is strongly dependent on fan-system interactions. An interesting fact is that the same fan when installed in different systems may have different acoustic performance. This is interesting since this means that when two fans are compared under testing conditions, e.g. ISO 10302, one might outperform the other, but when installed in a system, the inferior fan may actually end up being quieter. The argument that was made earlier about how local flow incidence and blade geometry affect the fan performance and cannot be captured by a fan performance curve also holds true for the acoustical fan performance. Local flow incidence and local turbulence levels, which may be different under installed conditions compared to testing conditions, do influence the noise emitted by the fan drastically.

![Graph showing broadband noise source model](source)

It would be highly beneficial to find a solution for predicting fan noise under installed conditions. Knowing that the broadband noise generated by fans originates from turbulent boundary layer flow over the blades suggests that an existing tool used for turbulent flow prediction, when embedded with a translator of turbulence-to-acoustics emissions, would reveal some very useful information about broadband noise. The boundary layer noise source model estimates the far-field sound generated by turbulent flow over a solid body at a low Mach number - which is indeed the case for flow through electronics cooling fans. The model uses approximate representation of the local surface pressure fluctuation in terms of turbulence quantities (turbulent kinetic energy, dissipation rate, and wall shear stress). By converting the local surface pressure fluctuations into sound intensity and integrating them over the fan surface, an approximate measure of the total surface acoustic power is obtained.
Conclusions

For forced air convection cooling to remain the workhorse of electronics thermal management, a closer look at the fan-system interaction with respect to airflow delivery and acoustics emissions are proposed and discussed. Local flow incidence and the true three-dimensional nature of the flow around the fan in a particular system do affect the fan performance and cannot be captured by incorporating a fan performance curve into the model. Alternative solutions are suggested by including more details about the fan geometry either mathematically (VBM) or by explicitly modeling the fan blades (MRF) as an integral part of the system. As a result, a more accurate estimate of the amount of airflow can be predicted to determine a more accurate estimate of the junction temperature. Moreover, the effects of the resulting airflow distribution over the fins and its effect on the local temperature variation can be accurately predicted and can therefore be used in further design optimization. It is also suggested that since broadband noise emitted by fans is largely due to turbulent boundary layer flow, detailed fan analysis within the system has the additional advantage of providing broadband noise behavior of the installed fan as a by-product. This allows the designer to compare the broadband acoustical behavior of different installed fan designs side by side to ultimately choose the most acoustically pleasing option.

9 Acoustics: Basic Physics, Theory, and Methods, P. Filippi, D. Habault, J.P. Lefebvre, A. Bergassoli, Academic Press.
10 The Dictionary for Human Factors/Ergonomics, James H. Stramler, Jr.

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