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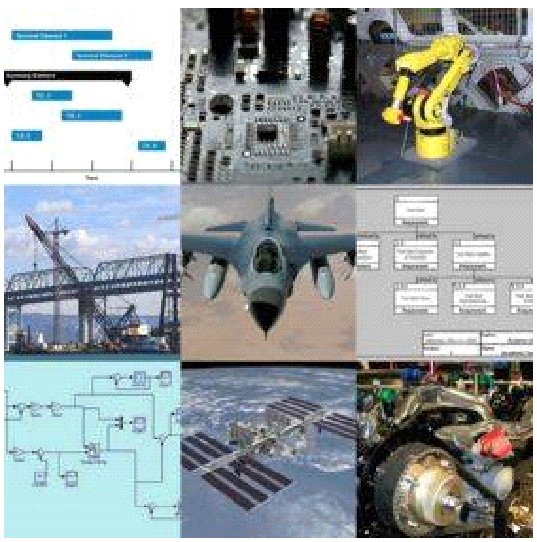

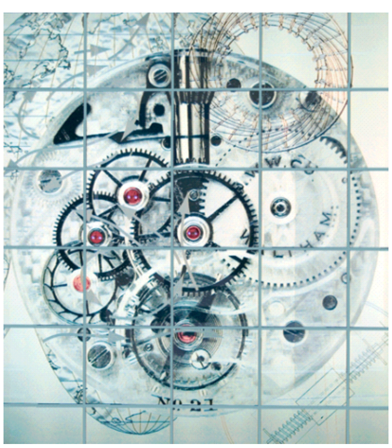

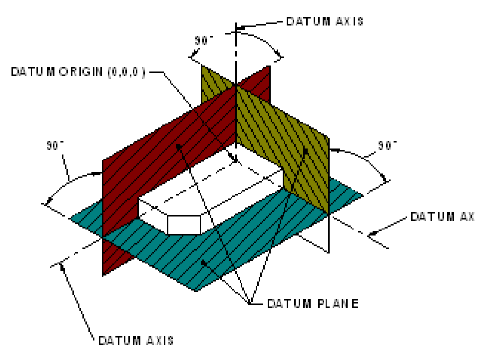

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Improving Fan System Performance

a sourcebook for industry

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Improving Fan System Performance: A Sourcebook for Industry has been developed by the U.S. Department of Energy's (DOE) Industrial Technologies Program and the Air Movement and Control Association International, Inc. (AMCA), a DOE Allied Partner. Industrial Technologies and AMCA International undertook this project as part of a series of sourcebook publications on motor-driven equipment under the BestPractices effort. Other topics in this series include compressed air systems, pumping systems, and motors and drives. For more information about the Industrial Technologies' BestPractices effort and AMCA International, see Section 3.

AMCA International is a not-for-profit association of the world's manufacturers of related air system equipment—primarily, but not limited to fans, louvers, dampers, air curtains, airflow measurement stations, acoustic attenuators, and other air system components—for industrial, commercial, and residential markets. The association's mission is to promote the health and growth of industries covered by its scope and the members of the association consistent with the interests of the public.

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Ron Wroblewski, Productive Energy Solutions

Prepared for: The United States Department of Energy
Air Movement and Control Association International, Inc.

Prepared by: Lawrence Berkeley National Laboratory
Washington, DC

Resource Dynamics Corporation
Vienna, VA

Section 1: Introduction to Fan Systems

Fans[1] are widely used in industrial and commercial applications. From shop ventilation to material handling to boiler applications, fans are critical for process support and human health. In the manufacturing sector, fans use about 78.7 billion kilowatt-hours[2] of energy each year. This consumption represents 15 percent of the electricity used by motors.[3] Similarly, in the commercial sector, electricity needed to operate fan motors composes a large portion of the energy costs for space conditioning.

Performance may range from "free air" to several pounds per square inch gage (psig)[4], with airflow from a few cubic feet per minute (cfm) to more than 1 million cfm. Pressures above 15 psig generally require air compressors, which are addressed in a separate sourcebook titled *Improving Compressed Air System Performance, A Sourcebook for Industry*.

In manufacturing, fan reliability is critical to plant operation. For example, where fans serve material handling applications, fan failure will immediately create a process stoppage. In industrial ventilation applications, fan failure will often force a process to be shut down (although there is often enough time to bring the process to an orderly stoppage). Even in heating and cooling applications, fan operation is essential to maintain a productive work environment. Fan failure leads to conditions in which worker productivity and product quality declines. This is especially true for some production applications in which air cleanliness is critical to minimizing production defects (for example, plastics injection molding and electronic component manufacturing).

In each case, fan operation has a significant impact on plant production. The importance of fan reliability often causes system designers to design fan systems conservatively. Concerned about being responsible for under-performing systems, designers tend to compensate for uncertainties in the design process by adding capacity to fans. Unfortunately, oversizing fan systems creates problems that can increase system operating costs while decreasing fan reliability.

Fans that are oversized for their service requirements do not operate at their best efficiency points. In severe cases, these fans may operate in an unstable manner because of the point of operation on the fan airflow-pressure curve. Oversized fans generate excess flow energy, resulting in high airflow noise and increased stress on the fan and the system. Consequently, oversized fans not only cost more to purchase and to operate, they create avoidable system performance problems. The use of a "systems approach" in the fan selection process will typically yield a quieter, more efficient, and more reliable system.

Fans

There are two primary types of fans: centrifugal and axial. These types are characterized by the path of the airflow through the fan. Centrifugal fans use a rotating impeller to increase the velocity of an airstream. As the air moves from the impeller hub to the blade tips, it gains kinetic energy. This kinetic energy is then converted to a static pressure increase as the air slows before entering the discharge. Centrifugal fans are capable of generating relatively high pressures. They are frequently used in "dirty" airstreams (high moisture and particulate content), in material handling applications, and in systems at higher temperatures.

[1] For the purposes of this sourcebook, the term "fan" will be used for all air-moving machines other than compressors.
[2] *United States Industrial Electric Motor Systems Market Opportunities Assessment*, U. S. Department of Energy, December 1998.
[3] Ibid.
[4] At standard conditions, a column of water 27.68 inches high exerts 1 psig of pressure. Equivalently, 1 inch of water gage = 0.036 psig.

Axial fans, as the name implies, move an airstream along the axis of the fan. The air is pressurized by the aerodynamic lift generated by the fan blades, much like a propeller and an airplane wing. Although they can sometimes be used interchangeably with centrifugal fans, axial fans are commonly used in "clean air," low-pressure, high-volume applications. Axial fans have less rotating mass and are more compact than centrifugal fans of comparable capacity. Additionally, axial fans tend to have higher rotational speeds and are somewhat noisier than in-line centrifugal fans of the same capacity; however, this noise tends to be dominated by high frequencies, which tend to be easier to attenuate.

◆ Fan Selection

Fan selection is a complex process that starts with a basic knowledge of system operating requirements and conditions such as airflow rates, temperatures, pressures, airstream properties, and system layout. The variability of these factors and other considerations, such as cost, efficiency, operating life, maintenance, speed, material type, space constraints, drive arrangements, temperature, and range of operating conditions, complicate fan selection. However, knowledge of the important factors in the fan selection process can be helpful for the purposes of reducing energy consumption during system retrofits or expansions. Often, a fan type is chosen for nontechnical reasons, such as price, delivery, availability, or designer or operator familiarity with a fan model. If noise levels, energy costs, maintenance requirements, system reliability, or fan performance are worse than expected, then the issue of whether the appropriate fan type was initially selected should be revisited.

Fans are usually selected from a range of models and sizes, rather than designed specifically for a particular application. Fan selection is based on calculating the airflow and pressure requirements of a system, then finding a fan of the right design and materials to meet these requirements. Unfortunately, there is a high level of uncertainty associated with predicting system airflow and pressure requirements. This uncertainty, combined with fouling effects and anticipated capacity expansion, encourages the tendency to increase the specified size of a fan/motor assembly.

Designers tend to protect against being responsible for inadequate system performance by "over-specifying." However, an oversized fan/motor assembly creates a different set of operating problems, including inefficient fan operation, excess airflow noise, poor reliability, and pipe/duct vibrations. By describing some of the problems and costs associated with poor fan selection, this sourcebook is intended to help designers and operators improve fan system performance through better fan selection and improved operating and maintenance practices.

Noise. In industrial ventilation applications, noise can be a significant concern. High acoustic levels promote worker fatigue. The noise generated by a fan depends on fan type, airflow rate, and pressure. Inefficient fan operation is often indicated by a comparatively high noise level for a particular fan type.

If high fan noise levels are unavoidable, then ways to attenuate the acoustic energy should be considered. Noise reduction can be accomplished by several methods: insulating the duct; mounting the fan on a soft material, such as rubber or suitable spring isolator as required to limit the amount of transmitted vibration energy; or installing sound damping material or baffles to absorb noise energy.

Rotational Speed. Fan rotational speed is typically measured in revolutions per minute (rpm). Fan rotational speed has a significant impact on fan performance, as shown by the following fan laws:

$$\text{Airflow}_{\text{final}} = \text{Airflow}_{\text{initial}} \left(\frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}}\right)$$

$$\text{Pressure}_{\text{final}} = \text{Pressure}_{\text{initial}} \left(\frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}}\right)^2$$

$$\text{Power}_{\text{final}} = \text{Power}_{\text{initial}} \left(\frac{\text{RPM}_{\text{final}}}{\text{RPM}_{\text{initial}}}\right)^3$$

Rotational speed must be considered concurrently with other issues, such as variation in the fan load, airstream temperature, ambient noise, and mechanical strength of the fan.

Variations and uncertainties in system requirements are critical to fan type and fan rotational speed selection. Fans that generate high airflow at relatively low speeds (for example, forward-curved blade centrifugal fans) require a relatively accurate estimate of the system airflow and pressure demand. If, for some reason, system requirements are uncertain, then an improper guess at fan rotational speed can cause under-performance or excessive airflow and pressure.

Airstream temperature has an important impact on fan-speed limits because of the effect of heat on the mechanical strength of most materials. At high temperatures, all materials exhibit lower yield strengths. Because the forces on shafts, blades, and bearings are proportional to the square of the rotational speed, high-temperature applications are often served by fans that operate at relatively low speeds.

Airstream Characteristics. Moisture and particulate content are important considerations in selecting fan type. Contaminant build-up on fan blades can cause severe performance degradation and fan imbalance. Build-up problems are promoted by a shallow blade angle with surfaces that allow contaminants to collect. Fans with blade shapes that promote low-velocity air across the blades, such as backward inclined fans, are susceptible to contaminant build-up. In contrast, radial tip fans and radial blade fans operate so that airflow across the blade surfaces minimizes contaminant build-up. These fans are used in "dirty" airstreams and in material handling applications.

Corrosive airstreams present a different set of problems. The fan material, as well as the fan type, must be selected to withstand corrosive attack. Also, leakage into ambient spaces may be a concern, requiring the fan to be equipped with a shaft seal. Shaft seals prevent or limit leakage from around the region where the drive shaft penetrates the fan housing. For example, in corrosive environments fans can be constructed with expensive alloys that are strong and corrosion resistant, or they can be less expensively constructed with fiberglass-reinforced plastic or coated with a corrosion-resistant material. Because coatings are often less expensive than superalloy metals, fan types that work well with coatings (for example, radial fan blades because of their simple shape) are widely used in corrosive applications; however, wear will reduce the reliability of coatings. Alternately, materials such as reinforced fiberglass plastics have been developed for fan applications and function effectively in many corrosive environments. However, there may be size and speed limitations for composite materials and plastic materials.

Airstreams with high particulate content levels can also be problematic for the fan drive train. In direct drive axial fans, the motor is exposed to the airstream. Sealed motors can be used in these applications but tend to be more expensive and, in the event of lost seal integrity, they are susceptible to expensive damage. In axial fans, belt drives offer an advantage by removing the motor from the airstream. In centrifugal fans, the particulate content is less of a factor because the motor or sheave can be located outside of the fan enclosure and connected to the impeller through a shaft seal. Gear drives are occasionally used in applications where speed reduction is required but the use of belt drives is unfeasible because of access or maintenance requirements.

In flammable environments, fans are usually constructed of nonferrous alloys to minimize the risk of sparks caused by metal-to-metal contact. In some applications, certain components of the fan can be fabricated out of spark-resistant materials. Fans that operate in flammable environments should be properly grounded, including rotating components, to minimize sparking because of static discharge.

Temperature Range. To a large degree, temperature range determines fan type and material selection. In high-temperature environments, many materials lose mechanical strength. The stresses on rotating components increase as the fan's operating speed increases. Consequently, for high-temperature applications, the fan type that requires the lowest operating speed for a particular service is often recommended. Radial blade fans can be ruggedly constructed and are frequently used in high-temperature environments. Component materials also significantly influence a fan's ability to serve in high-temperature applications, and different alloys can be selected to provide the necessary mechanical properties at elevated temperatures.

Variations in Operating Conditions. Applications that have widely fluctuating operating requirements should not be served by fans that have unstable operating regions near any of the expected operating conditions. Because axial, backward-inclined airfoil, and forward-curved fans tend to have unstable regions, these fans are not recommended for this type of service unless there is a means of avoiding operation in the unstable region, such as a recirculation line, a bleed feature, or some type of anti-stall device.

Space Constraints. Space and structural constraints can have a significant impact on fan selection. In addition to dimensional constraints on the space available for the fan itself, issues such as maintenance access, foundation and structural support requirements, and ductwork must be considered. Maintenance access addresses the need to inspect, repair, or replace fan components. Because downtime is often costly, quick access to a fan can provide future cost savings. Foundation and structural requirements depend on the size and weight of a fan. Selecting a compact fan can free up valuable floorspace. Fan weight, speed, and size usually determine the foundation requirements, which, in turn, affect installation cost.

If the available space requires a fan to be located in a difficult configuration (for example, with an elbow just upstream or downstream of a fan), then some version of a flow straightener should be considered to improve the operating efficiency. Because non-uniform airflow can increase the pressure drop across a duct fitting and will degrade fan performance, straightening the airflow will lower operating costs. For more information, see the fact sheet titled *Configurations to Improve Fan System Efficiency* on page 39.

An important tradeoff regarding space and fan systems is that the cost of floor space often motivates designers and architects to configure a fan system within a tight space envelope. One way to accomplish this is to use small-radius elbows, small ducts, and very compact fan assemblies. Although this design practice may free up floor space, the effect on fan system performance can be severe in terms of maintenance costs. The use of multiple elbows close to a fan inlet or outlet can create a costly system effect, and the added pressure drops caused by small duct size or a cramped duct configuration can significantly increase fan operating costs. System designers should include fan system operating costs as a consideration in configuring fan assemblies and ductwork.

Fan Performance Curves

Fan performance is typically defined by a plot of developed pressure and power required over a range of fan-generated airflow. Understanding this relationship is essential to designing, sourcing, and operating a fan system and is the key to optimum fan selection.

Best Efficiency Point. Fan efficiency is the ratio of the power imparted to the airstream to the power delivered by the motor. The power of the airflow is the product of the pressure and the flow, corrected for units consistency. The equation for total efficiency is:

$$\text{Total Efficiency} = \frac{\text{Total Pressure x Airflow}}{\text{bhp x 6,362}}$$

Where: Total Pressure is in inches of water
Airflow is in cubic feet per minute (cfm)
bhp is brake horsepower

An important aspect of a fan performance curve is the best efficiency point (BEP), where a fan operates most cost-effectively in terms of both energy efficiency and maintenance considerations. Operating a fan near its BEP improves its performance and reduces wear, allowing longer intervals between repairs. Moving a fan's operating point away from its BEP increases bearing loads and noise.

Another term for efficiency that is often used with fans is static efficiency, which uses static pressure instead of total pressure in the above equation. When evaluating fan performance, it is important to know which efficiency term is being used.

Region of Instability. In general, fan curves arc downward from the zero flow condition—that is, as the backpressure on the fan decreases, the airflow increases. Most fans have an operating region in which their fan performance curve slopes in the same direction as the system resistance curve. A fan operating in this region can have unstable operation. (See Figure 1-1.) Instability results from the fan's interaction with the system; the fan attempts to generate more airflow, which causes the system pressure to increase, reducing the generated airflow. As airflow decreases, the system pressure also decreases, and the fan responds by generating more airflow. This cyclic behavior results in a searching action that creates a sound similar to breathing. This operating instability promotes poor fan efficiency and increases wear on the fan components.

Fan Start-Up. Start-up refers to two different issues in the fan industry. Initial fan start-up is the commissioning of the fan, the process of ensuring proper installation. This event is important for several reasons. Poor fan installation can cause early failure, which can be costly both in terms of the fan itself and in production losses. Like other rotating machinery, proper fan operation usually requires correct drive alignment, adequate foundation characteristics, and true fit-up to connecting ductwork.

Fan start-up is also the acceleration of a fan from rest to normal operating speed. Many fans, particularly centrifugal types, have a large rotational inertia (often referred to as WR^2), meaning they require significant torque to reach operating speed.

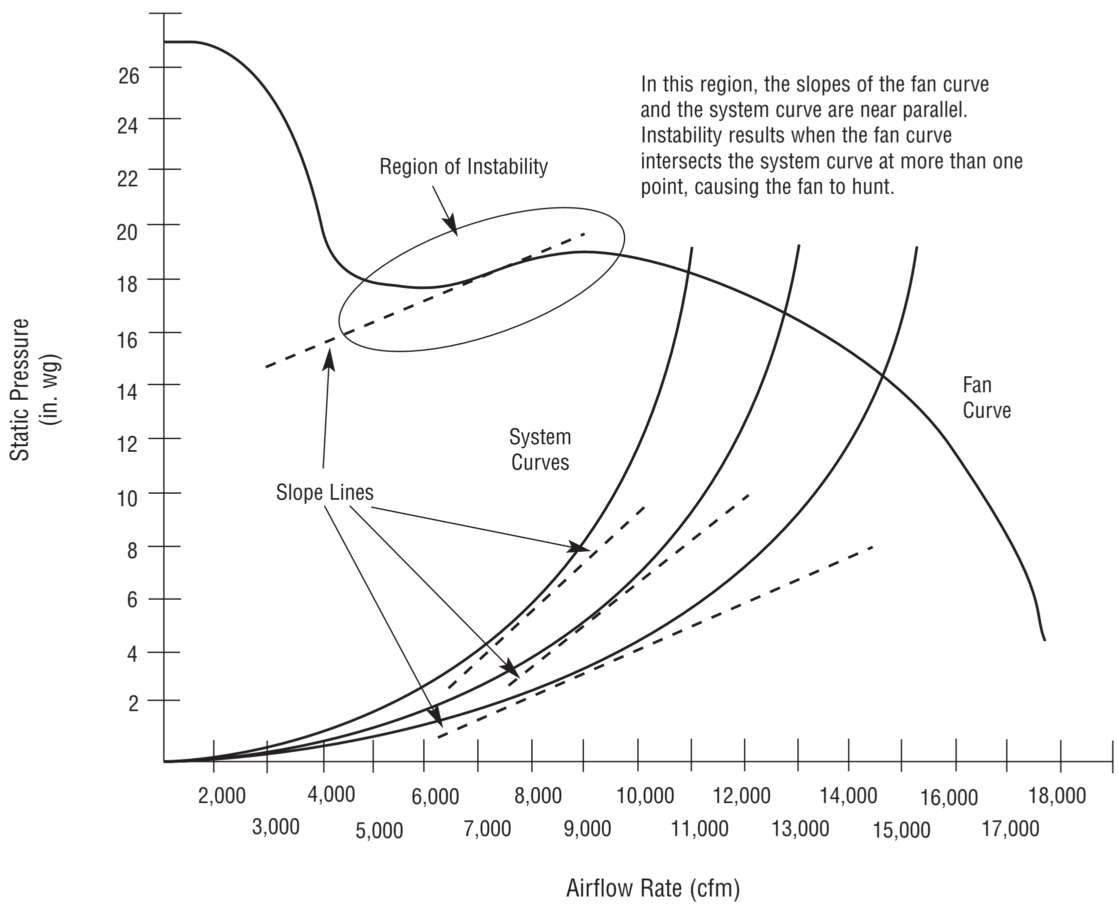

Figure 1-1. Region of Instability[5]

[5] Although fan system curves can have a static component, for the purposes of this sourcebook, system curves pass through (0,0).

In addition to the WR^2 load, the air mass moved by the fan also adds to the start-up torque requirements on the fan motor. Although rotational inertia is not typically a problem in
and air conditioning (HVAC
be a design consideration in
cations. Proper motor select
in ensuring that the fan can
operating speed and that, o
operates efficiently.

Because the start-up current
to 5 times the running curre
motor can be significantly r
fan under its minimum mec
allowing the motor to achie
speed more quickly than wl
In many applications, syster
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during start-up. For example
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flow (although in "non-over
power drops off after reachi
fans, the power tends to dec
flow. Consequently, for mos
large fan start-ups should be
downstream dampers closed
fan types, start-ups should b
dampers open. However, th
these guidelines, and the ac
the fan should be evaluated
soften the impact of a large

The power surges that acco
large motors can create pro
effects of a large start-up cu
problems and increased we
tem. In response to increasin
ment that minimizes the pro
large motor starts, electrical
turers are offering many different technologies, including special devices known as soft starters, to allow gradual motor speed acceleration. A key advantage of variable frequency drives (VFDs) is that they are often equipped with soft starting features that decrease motor starting current to about 1.5 to 2 times the operating current. Although VFDs are primarily used to reduce operating costs, they can significantly reduce the impact of fan starts on an electrical system.

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In axial fan applications, controllable pitch fans offer a similar advantage with respect to reducing start-up current. Shifting the blades to a low angle

shown by the corrected system curve in Figure 1-2.

The system effect can be minimized by configuring the system so that the flow profile remains as uniform as possible. However, if space constraints prevent an ideal system layout, then system effect consequences should be incorporated into the fan selection process. For more information on how to minimize losses, see the fact sheet titled *Configurations to Improve Fan System Efficiency* on page 39.