# FAN DESIGN

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# AERODYNAMIC CONSIDERATIONS IN FAN DESIGN

The following discussion describes the basic considerations in efficient axial flow fan design and illustrates features that will assist the reader in recognizing well-designed units.

## UNIFORM FLOW

One of the most important requirements of a fan wheel is that it must impart to the air stream a uniform velocity and pressure over its entire area. Any well-designed fan wheel is sure to have two characteristics:

1. The individual blades will be narrow at the tip, where the blade velocity is high, and will widen toward the hub, where more blade area is required due to lower blade velocity.

2. The angle of the blades to the plane of rotation will be minimum at the tip and increase as the hub is approached. Only with such calculated width and angle for each point on the blade can the design considerations of uniform velocity and pressure be accomplished.

The necessity for uniform flow and pressure is easily explained: If certain portions of the blade are not able to develop the pressure necessarily being carried by other portions of the blade, back flow of air at these points will occur. Such would be the case in the vicinity of the hub if a typical airplane propeller were adapted as a axial flow fan.

Unequal discharge velocities will waste power in excess velocity pressure. Since velocity pressure increases as the square of the velocity, unequal discharge velocities, when converted into velocity pressure, will average out to a higher overall velocity pressure than if the velocity were uniform over the discharge area. For this reason, fans which develop the greater part of their velocity and pressure near the blade tip will invariably fall short when efficiencies are considered.

For example, a fan of 80% efficiency with a uniform discharge velocity of 2000 FPM (10.2 m/sec) would have a velocity pressure of 0.25" (6.4 mm). Assume another fan in which 1/2 of the air volume being handled left the blower at 1000 FPM (5.1 m/sec) while the other half left at 3000 FPM (15.2 m/sec). The velocity pressure of the first half would be 0.06" (1.5 mm), while the velocity pressure of the second half would rise to 0.56" (14.2 mm), making the work done on the air, neglecting the static pressure, the equivalent of the average of the two, or 0.31" (7.9 mm) velocity pressure. Were this unit handling air at zero static pressure, its efficiency would be .25/.31 of the efficiency of the unit with uniform flow, or about 65% as compared to 80% for the fan with uniform flow.



$$C_L$$
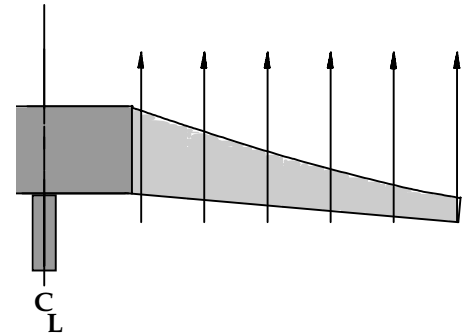
## *Uniform Velocity from hub to tip*

*One of the most important design considerations in a fan wheel is that it must impart to the air stream a uniform velocity and pressure over its entire area.*

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## HUB SIZE AND EFFECT

The question of how large a fan hub should be is commonly asked. The answer is simple: A hub must be large enough to pick up where the blades are no longer able to carry the load. As the radius is reduced and the center of the fan approached, the reduction in the speed of the blade section reduces the potential work which may be accomplished by the blade and increases the mean blade angle. Blade width will begin to increase abnormally and the blade angle will rise sharply until additional width and angle are no longer practical. At this point the hub must begin.

The hub serves two major (aerodynamic) purposes. It allows termination of the blades at a point where they would cease to function efficiently and it prevents back flow of air through the center.

If the hub is too large for the required performance, the result will be an increase in velocity pressure, due to the smaller net opening, and subsequent waste of power. If the hub is too small for the required performance, the result will be deterioration of the flow near the hub, possibly even a reversal of flow in this area.

Reference to the drawing on the following page will readily show the necessity of a hub of some proportion. As the centerline of the wheel is approached, the width of the blade becomes infinite. For practical reasons, it is evident that the hub in this example should start at or near the "RADIUS = 2" point to avoid excessive blade depth.

The fan hub must, of course, also serve a structural function in connecting the blades and imparting rotation to them. The hub size required by the aerodynamic considerations discussed in the preceding paragraphs would result in an extremely heavy (and expensive) structural member. For this reason, fan manufacturers usually provide a hub that is inadequate from an aerodynamic point of view. Moore solves this problem by providing two hub designs for each series of fan: A smaller structural hub and a properly proportioned aerodynamic hub referred to as the Air Seal.
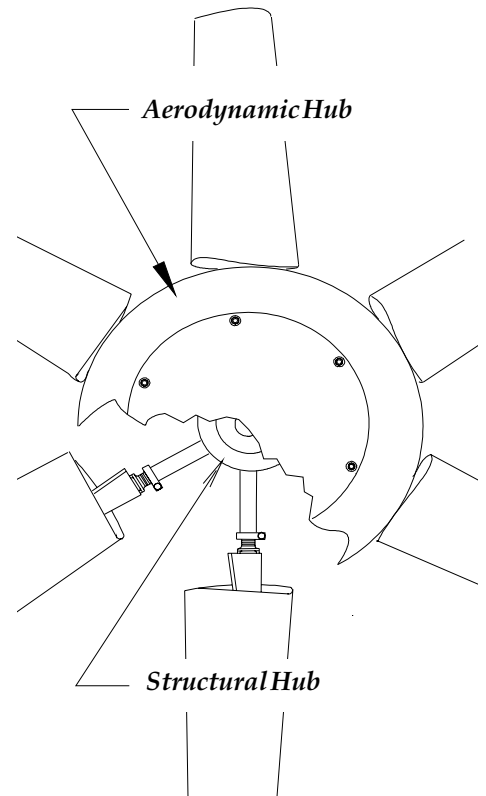
## BLADE SECTION

The airfoil shape of the fan blade should be selected on the basis of high efficiency -- that is, high lift and low drag -- as well as the lift coefficient desirable in the particular instance. The abruptness at which stalling occurs should also be considered. Fortunately, extensive studies have been made on the performance of thousands of shapes of airfoils. This information is readily available and furnishes complete performance data on each section, considering lift, drag, angle of attack, and other test data. Such information is invaluable to the fan designer since these known characteristics enable him to predict accurately the performance of the wheel being designed.
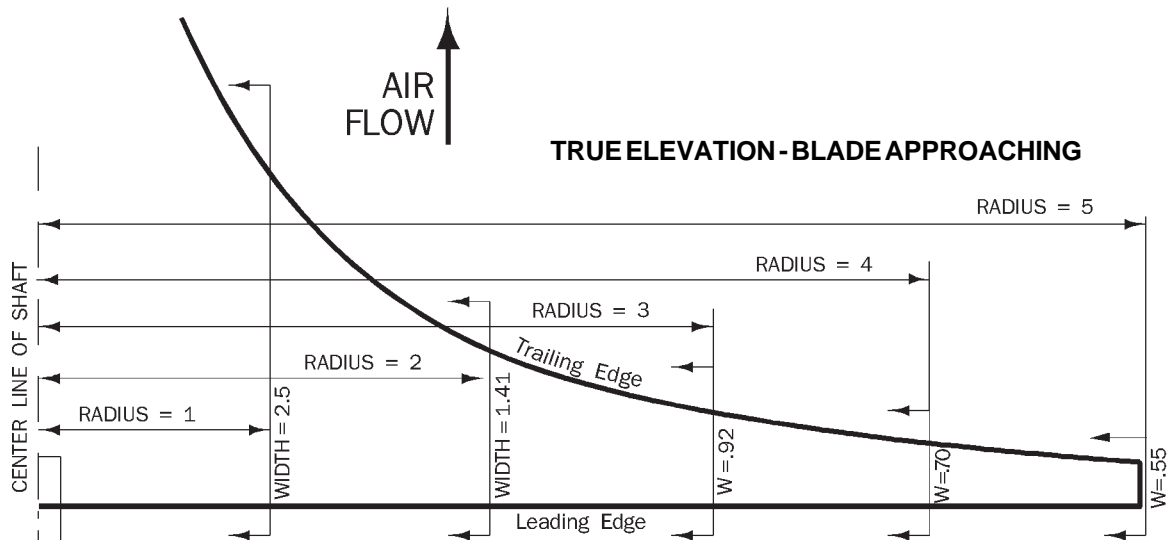
## PITCH AND BLADE ANGLE

The term "pitch" is defined as the advance of the air stream per revolution of the fan wheel. Pitch may be expressed in feet per revolution but, for convenience and in order to make it a dimensionless quantity, pitch will be referred to here in terms of hub diameters. For example, a fan with an (aerodynamic) hub diameter of 4 feet, operating at a pitch of 2 hub diameters, would be moving air axially through the wheel at a rate of 8 feet per revolution of the wheel.

Blade angle, or blade setting, is not to be confused with pitch. Blade angle denotes the angle of the blade with the plane of rotation at a given point on the blade. It is important to note that, for uniform flow and constant pitch, every point on the blade, from



*Aerodynamic Hub*

*Structural Hub*

*Moore avoids compromising on hub size by providing two hubs! — Each properly proportioned for its function.*

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# BLADE ANGLE AND WIDTH FOR AERODYNAMIC DESIGN

AIR FLOW

**TRUE ELEVATION - BLADE APPROACHING**

RADIUS = 5

RADIUS = 4

RADIUS = 3

RADIUS = 2

RADIUS = 1

CENTER LINE OF SHAFT

WIDTH = 2.5

WIDTH = 1.41

W = .92

W=.70

W=.55

Trailing Edge

Leading Edge

The drawing above represents a front elevation of a blade blowing upward, rotating toward the observer about the center line of the driving shaft, shown at left. The leading edge is assumed to be straight and the increase in required width as the center is approached is taken up by the trailing edge.

**VECTOR DIAGRAMS**

V U RADIUS = 1   V U RADIUS = 2   V U RADIUS = 3   V U RADIUS = 4   V U RADIUS = 5
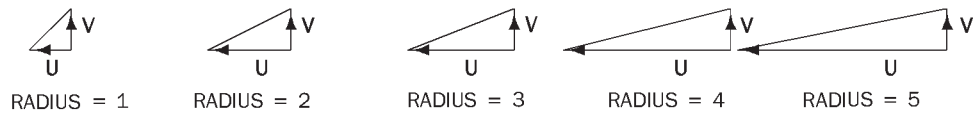
The vector diagrams above show the relative velocity of the blade and the air, taken at the sections indicated. The vertical vectors represent air velocity at each radius and are equal as required by efficient design. The horizontal vectors represent the speed of the blade at each radius and decrease from tip to center. The resultant vectors represent the blade angle and resultant velocity of the blade at each radius for a blade which is only free wheeling and performing no work on the air stream.

**CROSS SECTION OF BLADE SHOWING BLADE ANGLE**

WIDTH = 2.50

WIDTH = 1.41

WIDTH = .92

WIDTH = .70

WIDTH =.55

RADIUS = 1        RADIUS = 2        RADIUS = 3        RADIUS = 4        RADIUS = 5

The blade sections above portray to scale the blade angle at each radius required to permit unobstructed air flow, based upon the assumption of free wheeling. Some increase in angle at the tip and a considerable increase near the center would be necessary if the blade were to exert work upon the moving air stream. These blade sections also show the width required at each radius to develop an equal pressure on the air stream from the tip inward.

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diameter of 4 ft (1.2 m), operating at a pitch of 2 hub diameters, would be moving air axially through the wheel at a rate of 8 feet (2.4 m) per revolution of the wheel.

Blade angle, or blade setting, is not to be confused with pitch. Blade angle denotes the angle of the blade with the plane of rotation at a given point on the blade. It is important to note that, for uniform flow and constant pitch, every point on the blade, from the hub to the tip, must have a different angle.
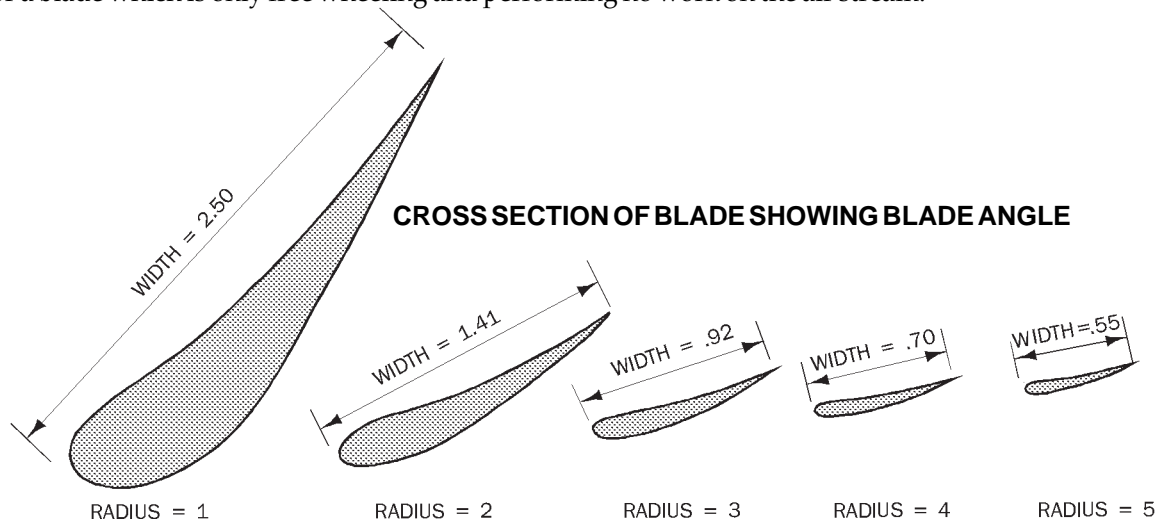
If we assume a condition in which a wheel is operating at a given speed with air being forced through the wheel at a given velocity, and the wheel itself exerting no work on the air stream, the blade angles at various points on the blade will be approximately as illustrated on the preceding page.

In this chart, "V" represents the velocity of the air, which is constant over the entire blade length. The letter "U" represents the relative direction between the blade and air stream.

The preceding discussion, as well as the illustration, is based on the blade merely free-wheeling in the air stream, neither assisting or retarding the air flow. In order for the blades to produce work, an additional angle must be provided. This is called the angle of attack, generally from two to six degrees, and is additive to the relative angle described above. In addition, another angle also must be added to each section of the blade to compensate for the deflection imposed upon the air stream by the wheel. As the air is deflected in passing through the wheel, 1/2 of the total deflection angle at each radius of the blade must be added to the angle already obtained. Since the deflection is greater nearer the hub, an added angle which may be as great as 25 degrees in itself would be required at the hub, while only a minimum increase of 5 or 10 degrees in angle would be made at the tip. This results in a great deal of twist in a properly designed blade.

If we assume a fixed velocity through the wheel, an increase of two or three degrees would probably be sufficient to cause stalling and a breakdown of flow. In actual operation, increasing the angle of the blade would increase the air flow to a limited extent and stalling would probably not occur as readily as in the previous example. See Section 4, "Operation" in the Owner's Manual for a detailed discussion of the effects of increasing blade angle.
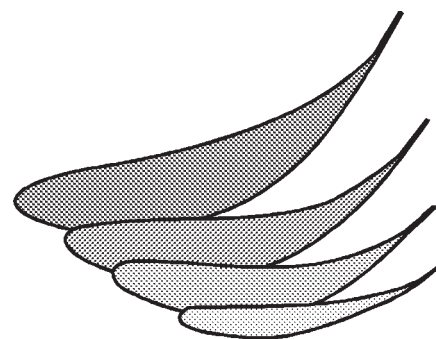


## *Aerodynamic Blade Design*

*The drawing above represents equidistant profiles of an end view of the blade. Note that from the thin, narrow tip to the thick, cambered root, each blade has, at design pitch, the proper combination of airfoil camber, width and angle to provide uniform pressure and velocity from the hub to the tip. This is the criterion of efficient axial flow fan design.*

**BLADE PLAN FORM**

Although the lift coefficients of different airfoil sections vary, it is necessary that a fan for a given duty have a total blade width at each point on the blade which is determined by the requirements of the angle of attack at the lift coefficient chosen. The illustration on page 3 is based on the fact that pressure exerted by the blade is proportional to the square of the speed, and shows graphically the blade form necessary to furnish uniform pressure from near the center to the tip of the blade.

It is evident that the blade width must increase as the hub is approached. Blades which are of uniform width throughout their length must, of necessity, carry too much blade surface at the tip or too little surface at the hub. Such construction would, of course, lead to inefficiencies. If the surface at the tip is too great, efficiency will be lost due to the excess blade surface and subsequent increased drag. If the surface near the hub is too small, sufficient blade surface will not be available to maintain proper flow conditions, and flow will be deficient, non-existent, or in reverse, and efficiency will plummet.

*Extruded blades (which must, of necessity, be of uniform width) cannot match the efficiency of blades that are properly proportioned.*

## NUMBER OF BLADES

The number of blades in a fan wheel is not important, but the area of the total blade surface at each radius is vital: that is, individual blade area for each increment along the blade times the number of blades. Blade widths are generally limited by physical conditions in order to keep the fan wheel from becoming too deep. Two wide blades would operate as efficiently as eight narrow blades having the same total width at each radius. For the sake of simplicity, however, reference to blades hereafter will indicate blades of given sizes as used in Moore Class 5000 fans. Here the optimum number of blades providing the required blade surface may be used for any set of conditions so that it is unnecessary to operate the blades of a unit under either overload or underload conditions, as would be necessary were the number of blades fixed.

Because of the importance of avoiding either excess or insufficient blade area, it is an advantage to be able to select any number of blades up to the physical limitation of the unit rather than being limited to only even numbers of blades.
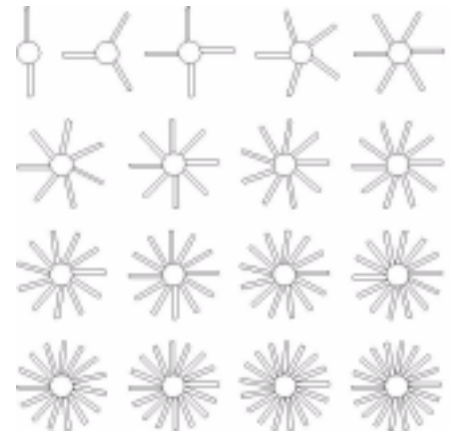
*Fans with a fixed number of blades or whose blades must be increased in pairs, must often provide either excess or insufficient blade area.*

## BLADE SPEED AND RPM

Proper wheel design must be closely correlated with blade speed since the total pressure furnished by any wheel is proportional to the square of the RPM. The hub diameter, pitch, blade angle, number of blades, and deflection of the air stream all depend upon the RPM of the unit. For a given performance, a lower RPM will require a greater number of blades for the same hub diameter. Still lower RPM may be obtained in a higher series with a larger hub diameter since it is necessary that the slowest portion of the blades, which is the portion next to the hub, be traveling at sufficient speed and have sufficient surface to accomplish the required performance. As a result, the lower the speed, the larger the hub required to achieve the necessary peripheral velocity. In a given wheel under fixed conditions, an increase in RPM will result in a horsepower increase proportional to the cube of the RPM. For this reason, variable speed units cannot be expected to achieve greatly increased air flow without excessive horsepower gain.

## LIMITATIONS OF FAN WHEELS

There are two principal limitations in the design of a fan wheel operating at a fixed speed:

1. Blade surface may be increased by adding blades with corresponding increase in potential total pressure until a point is reached where the blades become so close together that there is not sufficient air between them to allow their full effect to be utilized. Blade interference then occurs, starting at the hub and progressing outward as additional blades are added.

2. Of equal importance is the deflection, or rotation of the air stream imparted by the wheel in accomplishing its work. The higher the pressure against which the wheel may work for a given velocity, the greater the deflection of the air stream, which is accompanied by a reduction in the pressure potential of the blades. This is set out in further detail in the following paragraphs.

## DEFLECTION OF DISCHARGE

Any fan wheel, in imparting motion to the air in an axial direction, must also impart motion in the direction of the rotation of the wheel. The vector sum of these two velocities is the total velocity imparted to the air stream. The word "velocity" in fan rating signifies only the axial velocity of the discharge. It is to be understood that unless guide vanes are used, the actual velocity must in all cases exceed the axial velocity, as the actual velocity is the vector sum of the axial velocity and the rotational velocity. Any increase in velocity above the axial velocity represents wasted power. The illustration at left shows the manner in which these various velocity components are developed.

Assume a fan wheel providing an axial velocity of 2000 FPM (10.2 m/sec) with a deflection of 45° at a certain radius. This deflection would indicate a rotational component equal to the axial velocity. The actual velocity, or vector sum of the two, would be the square root of the sum of the squares of the two, or 2828 FPM (14.4 m/sec). The axial velocity corresponds to a velocity pressure of 0.25" (6.4 mm). However, 2828 FPM (14.4 m/sec) corresponds to 0.50" (12.7 mm) velocity pressure. As a result, one-half of the work utilized in bringing this air to the velocity of 2828 FPM (14.4 m/sec) is wasted, as only the axial velocity determines the volume furnished by the wheel.

The deflection of discharge at any radius on any axial flow fan wheel may be estimated by calculation of the following formula:

$$\text{Rotational Component} = \frac{\text{Total Pressure}}{\text{Blade Speed x Density}}$$

Note:  Total Pressure is in pounds per square foot
Blade Speed is in feet per second
Density is in slugs per cubic foot. (lbs/ft³/32.2)

The total pressure set out above is that developed by the wheel. The blade speed is the speed in feet per second at the radius being considered. The rotational component so obtained must be combined with the axial velocity to determine the deflection angle and losses.

It should be noted that deflection is theoretically minimum at the tip and increases to maximum at the hub, which is the limiting point. In the event of excessive tip clearance being present, the deflection may be higher at the tip than further in on the blade. This is due to back flow reducing normal axial flow. Reduction of the axial component with constant rotational component will increase the angle of deflection. If backflow and normal flow are equal (that is, zero flow) 90 degrees deflection will result at the tip.

Under certain conditions such as high static pressures and low discharge velocities, the angle of deflection may become so great that the air will rotate with the wheel rather than being discharged in a reasonably axial direction. Such conditions, of course are to be avoided as performance will deteriorate rapidly after the critical deflection angle is reached.

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