Stall Detection and Control in Commercial and Industrial Fans

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Lisa Cherney

Education Manager, AMCA International

Webinar Moderator

- Joined AMCA in February 2019
- Responsible for development of AMCA's education programs; staff liaison for the Education & Training Committee
- Projects include webinars, AMCA's online learning platform programming, presentations at trade shows, PDH/RCEP account management, and AMCA's Speakers Network

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Dr. Geoff Sheard

President, AGS Consulting, LLC

- Over 40 years experience in the aerodynamic and mechanical design of rotating equipment.
- International expert in fan technology and development of high efficiency fans for commercial and industrial application.
- Holds a BEng in mechanical engineering, a DPhil in aerodynamics plus a DSc awarded for the application of aerospace design techniques in commercial and industrial fan design.
- Past President of AMCA and Chairman of the FAN 2012, 2015, 2018 and 2022 conference organizing committee.

Stall Detection and Control in Commercial and Industrial Fans

Purpose and Learning Objectives

The purpose of this presentation is to provide an understanding of the mechanical consequences of aerodynamic stall and outline the options available for avoiding aerodynamic stall.

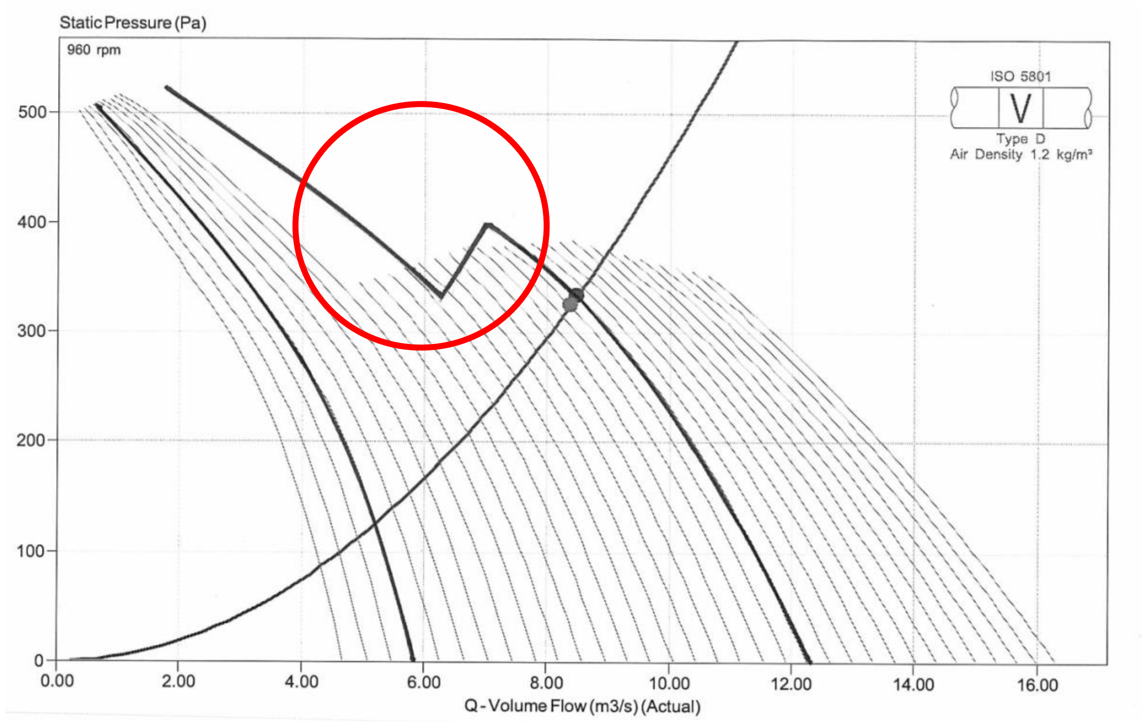
At the end of this presentation you will be able to:

- Explain what stall is, and why it matters more in axial than centrifugal fans.
- Outline why some axial fans able to operate in stall long-term while others fail quickly.
- Identify what strategies are available when selecting axial fans to avoid stall.
- Describe how to monitor a fan to ensure it is not running in a stalled condition.

Agenda

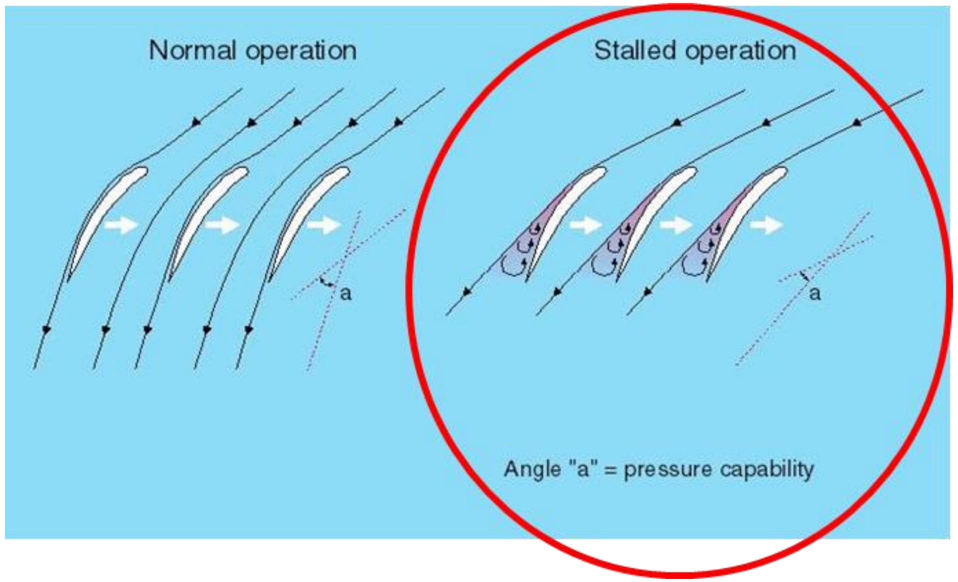
- Aerodynamic Stall
- Pressure Pulses
- Solutions to Accommodate Pressure Pulses
  - Selection Strategy 1
  - Selection Strategy 2
  - Selection Strategy 3
- Anti-Stall Casing Treatment
- Mechanical Failure Mechanism
- Safety Factors
- Example Practical Selection & Cost Implications
- Conclusions & Supplementary Material

What is Aerodynamic Stall?



When a fan exceeds its pressure developing capability, there is a sudden drop in the pressure the fan is able to develop. This sudden drop is referred to as stall.

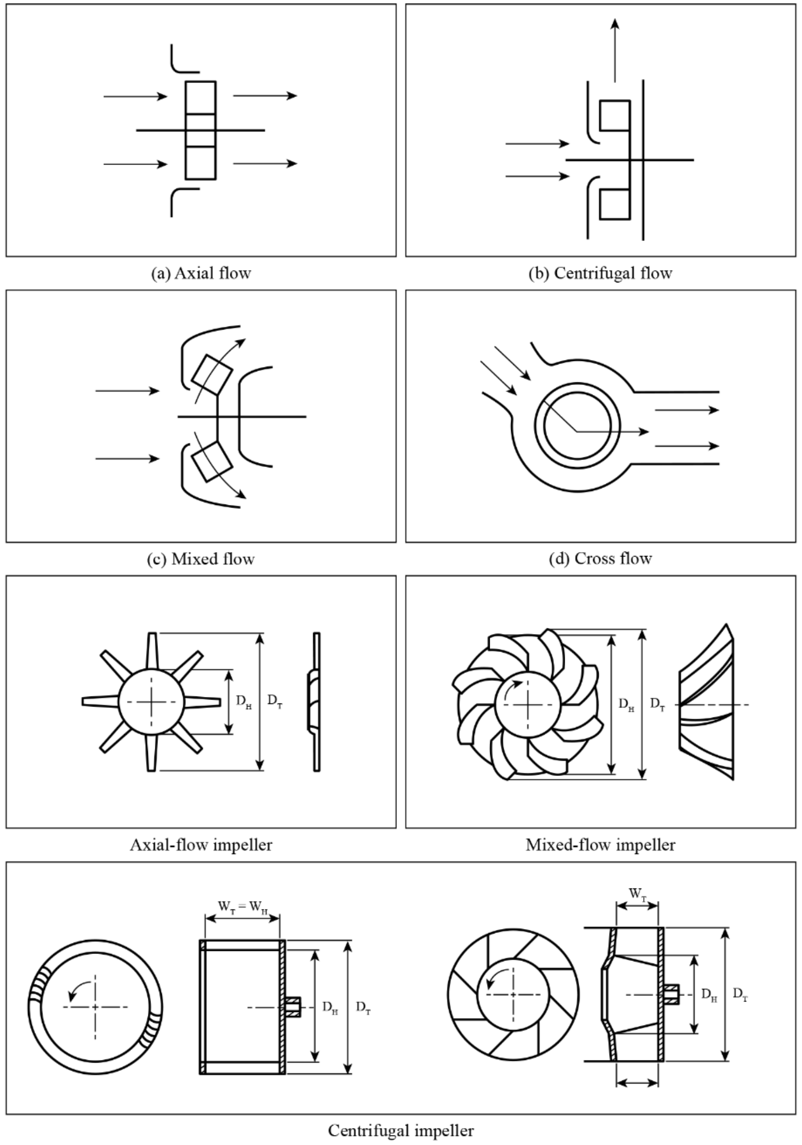
What Happens When a Blade Stalls?



- When a fan stalls, the flow “breaks away” from the fan blades.
- The break away is accompanied by turbulence that results in vibration of the fan blades.

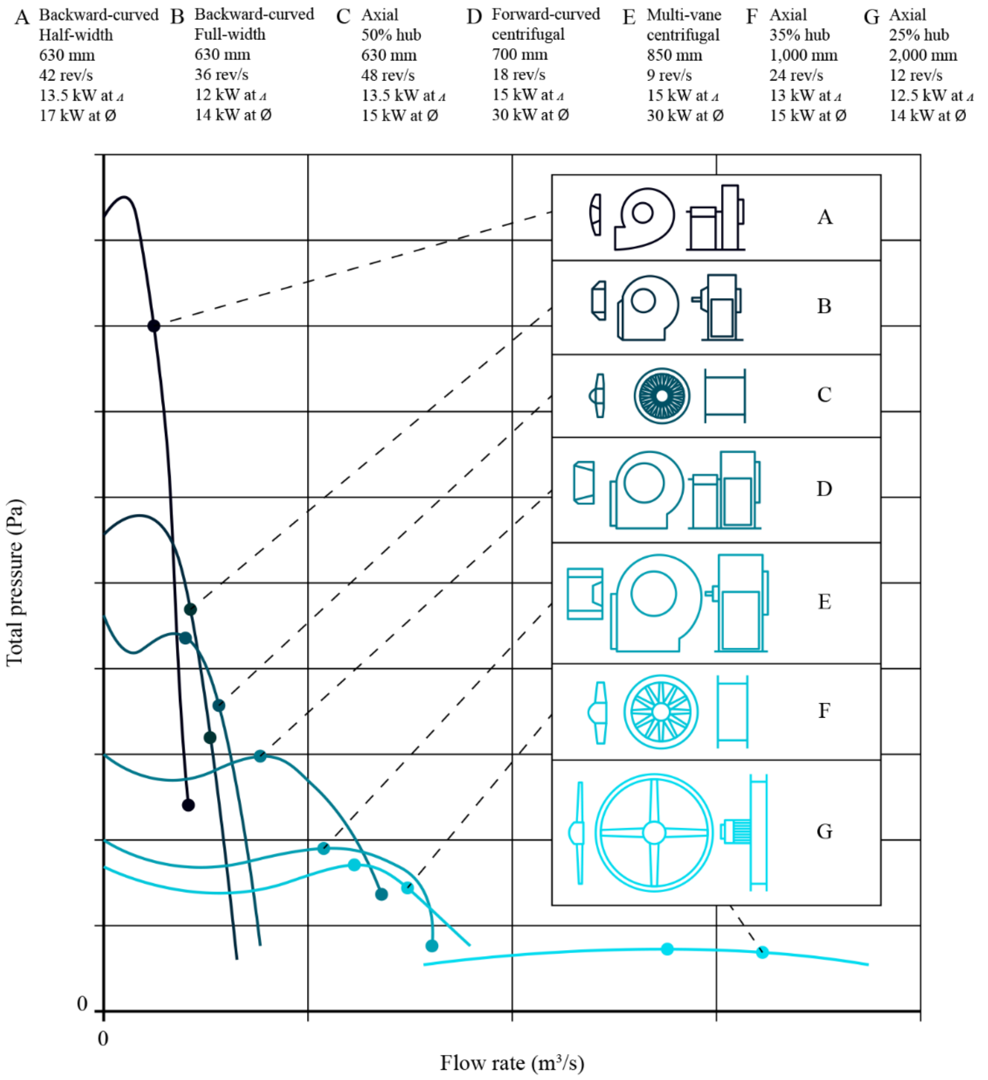
Different Types of Fans

- The different types of fans may be characterized in terms of inlet and outlet flow direction.
- Axial fans have flow entering and exiting axially.
- Centrifugal fans have flow entering axially, but leaving radially.
- Flow velocity through a fan reduces as a fan approaches stall. As flow exits radially in a centrifugal fan, this is less of an issue. However, in an axial fan it is a significant issue.



Axial vs Centrifugal Fan Stall

- The higher pressure centrifugal fans have continuously rising characteristics, and so if they suffer aerodynamic stall at all, it is less severe.
- Although axial fans have a lower pressure-developing capability, their characteristics rises from free-delivery back to a peak, and then falls. Hence, they have a clear and severe aerodynamic stall point.



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Why Do Fans Stall?

- Fans stall when their maximum pressure development capability is exceeded.
- Fans can stall transiently as a train passes a tunnel ventilation shaft.
- When a train moves through a tunnel, there is a positive pressure pulse as it approaches a ventilation shaft and a negative pressure pulse as it departs.
- Tunnel ventilation fan selections must take into account the additional pressure-developing requirement associated with typically a +/- 300 Pa pressure pulse.

Why Do Fans Stall?

- A factor that is resulting in fan stall becoming more common is the increasing magnitude of pressure pulses in metro systems as a consequence of a trend towards the use of platform screen doors.
- Platform screen doors at metro stations screen the platform from the train. They are a relatively new addition to metro systems, and are today in wide use in Asia and Europe.

Example of Platform Screen Doors

Platform Screen Doors

- The effect of platform screen doors is to prevent the air being pushed in front of an approaching train from escaping through the stations.
- The effect of constraining the tunnel air inside the tunnel itself is to increase the magnitude of the pressure pulse generated by the train.
- With platform screen doors a typical pressure pulse is between +/- 600 and +/- 700 Pa, approximately double the historic norm.
- A consequence of the larger pressure pulses is that tunnel ventilation fans are more likely to be driven into stall as a train passes a ventilation shaft.

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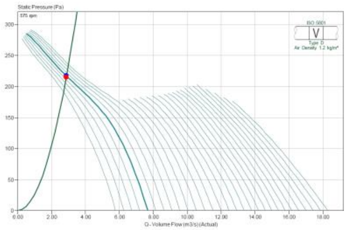
Fan Operation

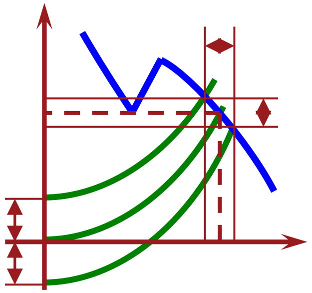
- It is vital that the pressure pulse is known at the time the fans are selected.
- If the pressure pulse is underestimated and the fans are driven into stall every time a train passes, then the fan blades will fail mechanically.
- The exact time taken for the blades to fail mechanically is dependent on the mechanical design of the fan and the severity of the aerodynamic stall.
- The severity of aerodynamic stall is governed by the magnitude of fan design point pressure and the size of the pressure pulse.

Solutions to Allow for Pressure Pulse

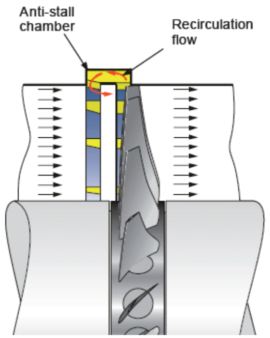
- Selection strategy 1: To choose a fan with a non-stalling blade angle.



- Selection strategy 2: To choose a fan with enough reserve on the pressure.

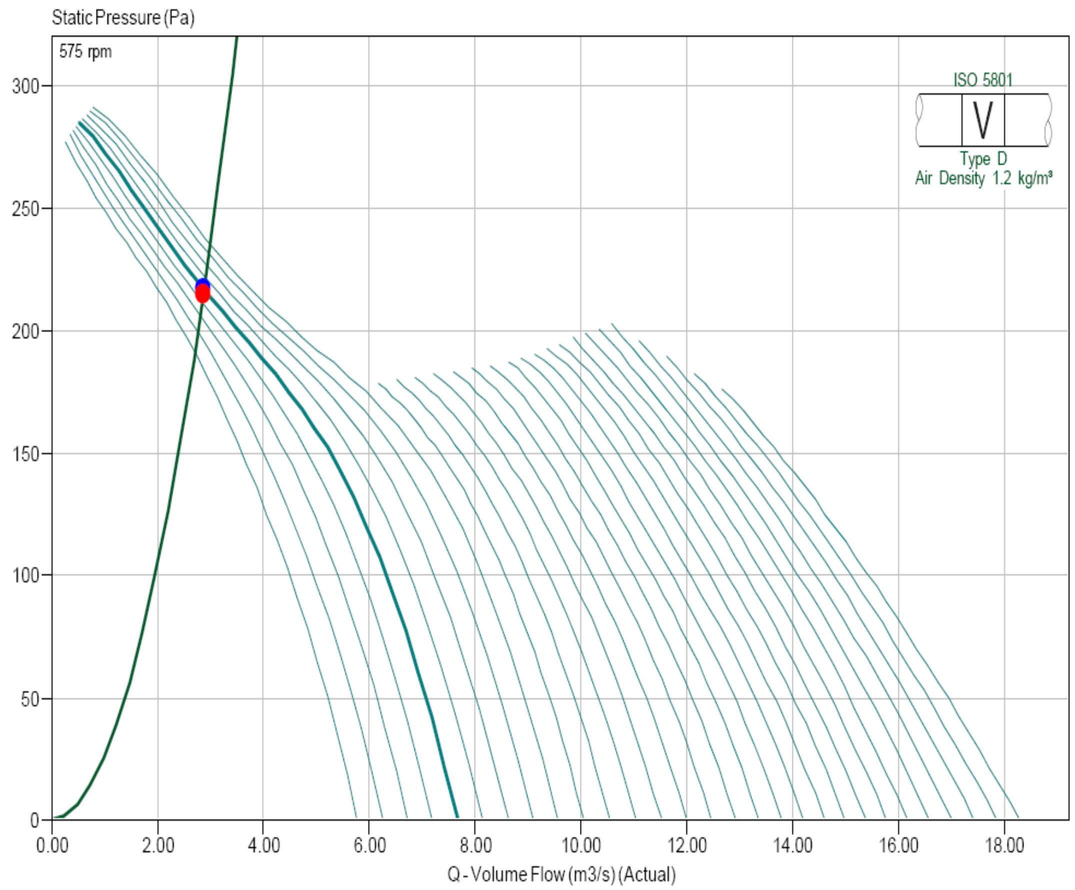


- Selection strategy 3: To use a fan with an anti-stall device.



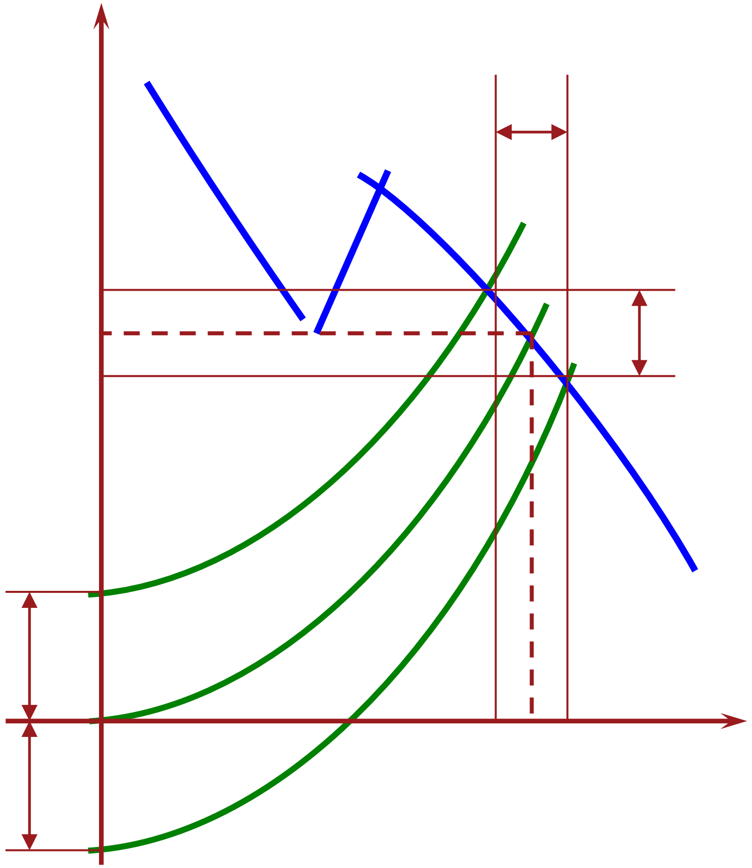
Selection Strategy 1

- Axial fans have what is known as "non-stalling" blade angles.
- When the blade angle is below approximately 18 degrees, the fan is aerodynamically so lightly loaded that it does not stall.
- Fans with a non-stalling blade angle have a continuously rising pressure characteristic back to zero flow.
- Lightly loaded fans are relatively large, low speed fans, in comparison with highly loaded fans.



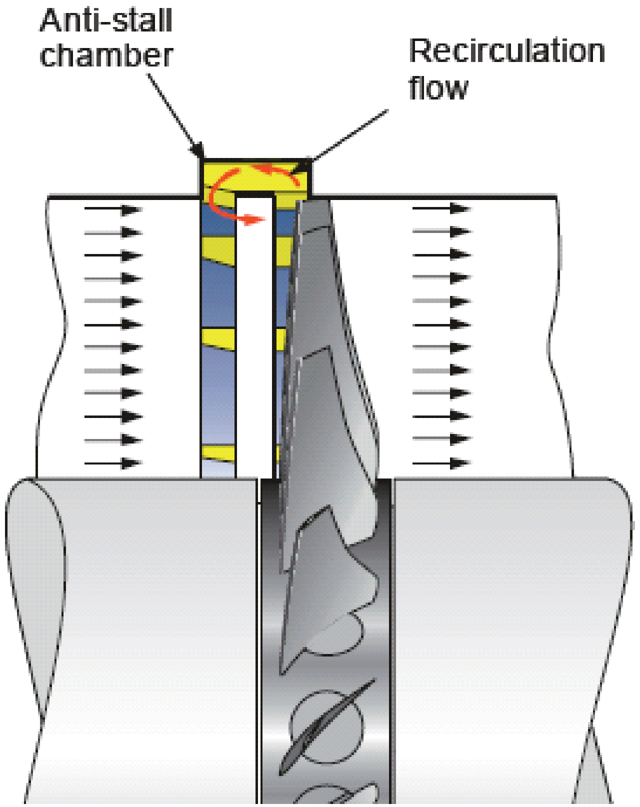
Selection Strategy 2

- If the magnitude of a pressure pulse is known at the time that the fan is selected, then it is possible to select a fan with sufficient pressure developing capability to accommodate the pressure pulse without the fan being driven into stall.
- This selection strategy relies on accurate knowledge of the duty point and size of pressure pulses both at the time of design and over the in-service life of the fan.



Selection Strategy 3

- If the duty point and magnitude of pressure pulses though the in-service life of a fan can not be known with certainty, then the fan can be protected with an anti-stall casing treatment.
- Anti-stall casing treatments modify the fan characteristic, with the consequence that a fan that would suffer aerodynamic stall without an anti-stall device has a continuously rising pressure characteristic back to zero flow with an anti-stall device.



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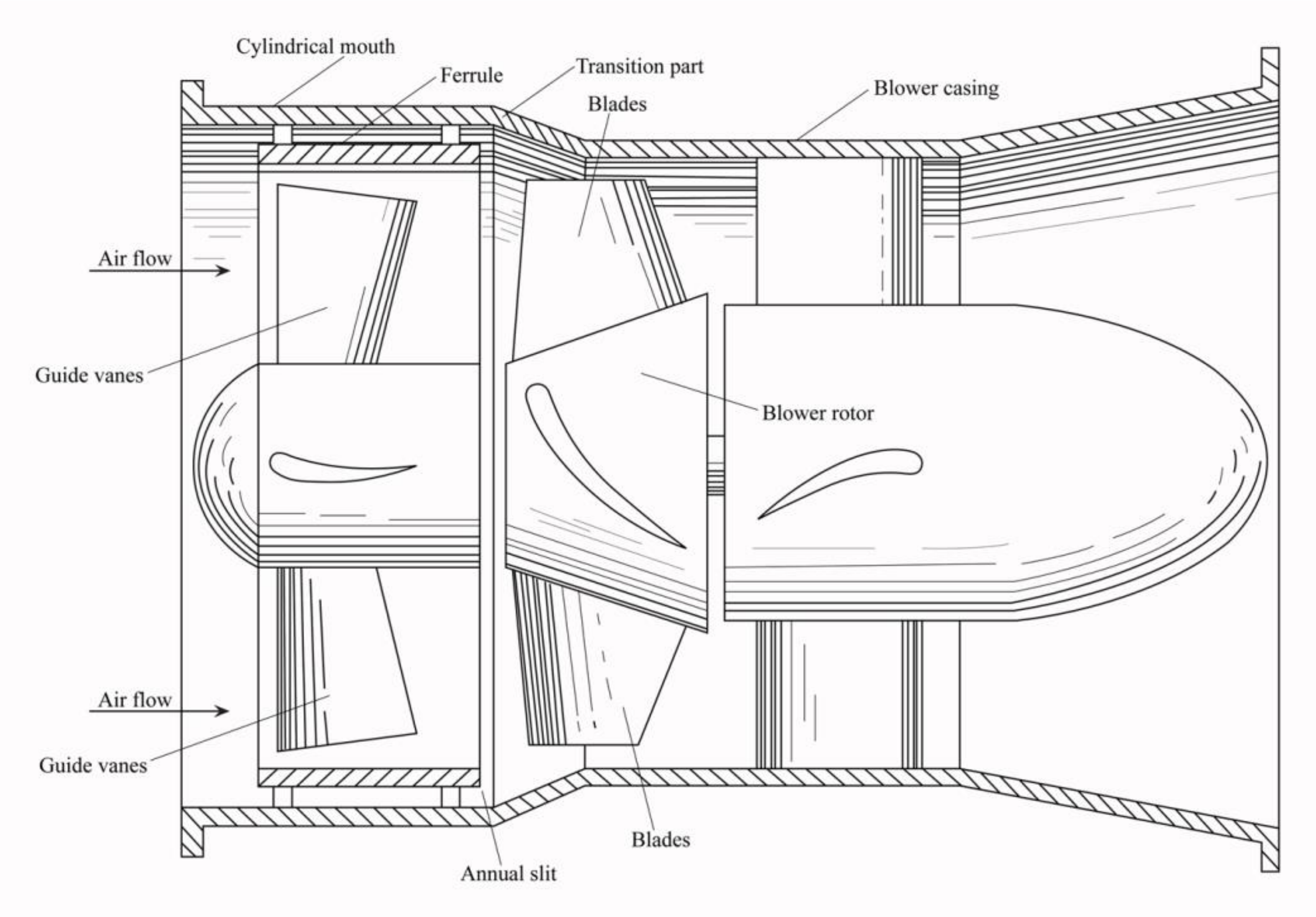
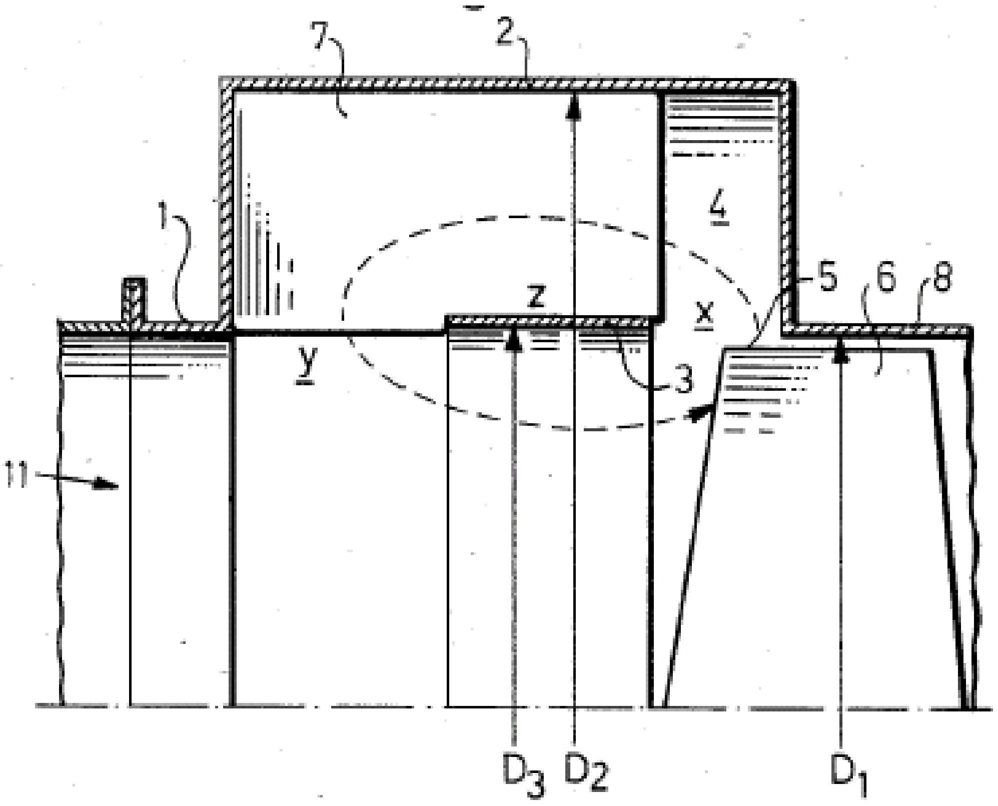
Today’s Anti-Stall Casing Treatments

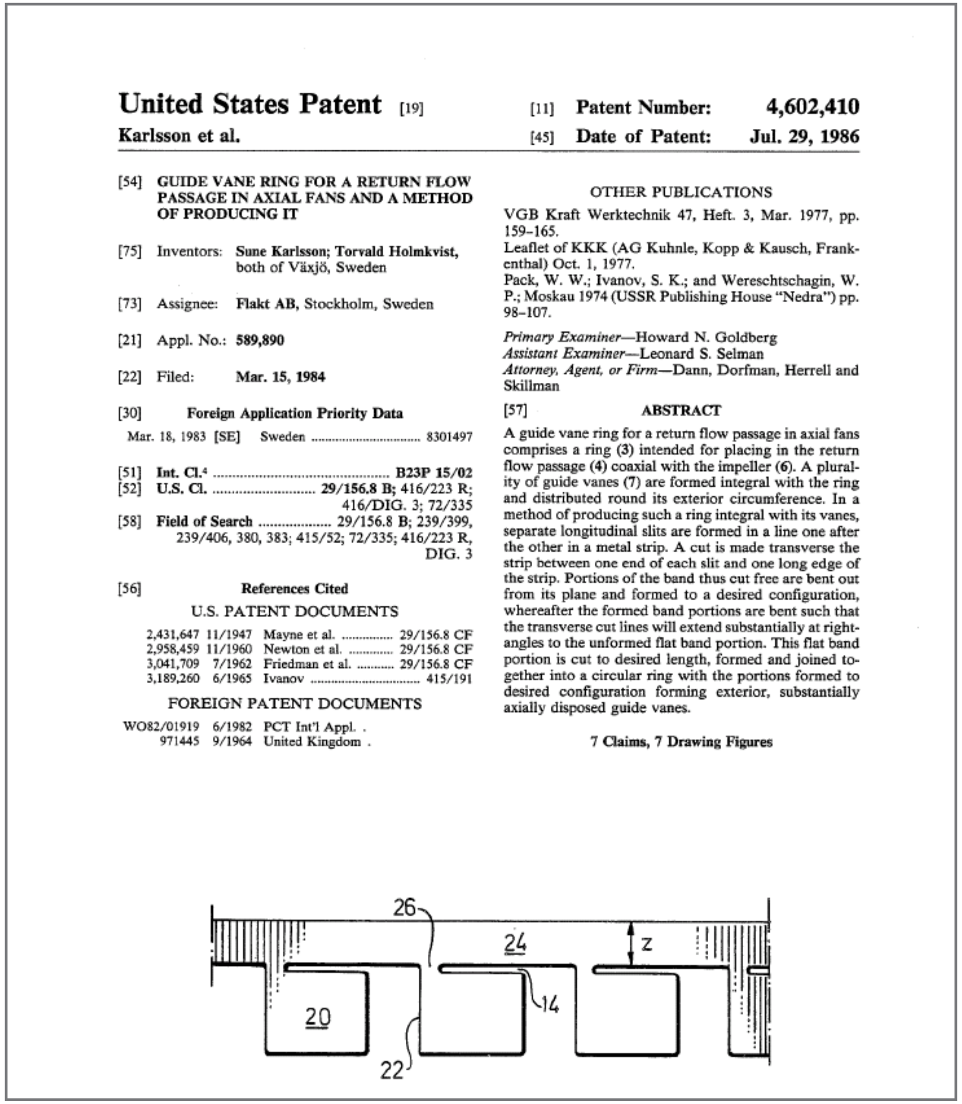
- The first anti-stall casing treatment required static vanes to be fitted upstream of the fan, in addition to a casing treatment.
- Today’s anti-stall casing treatment incorporates the static vanes into the casing treatment, and so is a more practical implementation of the anti-stall concept.

The First Anti-Stall Casing Treatment



Today's Anti-Stall Casing Treatment





United States Patent [19]
Karlsson et al.

[11] **Patent Number: 4,602,410**
[45] **Date of Patent: Jul. 29, 1986**

[54] **GUIDE VANE RING FOR A RETURN FLOW PASSAGE IN AXIAL FANS AND A METHOD OF PRODUCING IT**

[75] Inventors: **Sune Karlsson; Torvald Holmkvist,** both of Växjö, Sweden

[73] Assignee: **Flakt AB,** Stockholm, Sweden

[21] Appl. No.: **589,890**

[22] Filed: **Mar. 15, 1984**

[30] **Foreign Application Priority Data**

Mar. 18, 1983 [SE] Sweden 8301497

[51] **Int. Cl.**[4] **B23P 15/02**
[52] **U.S. Cl.** .... **29/156.8 B;** 416/223 R; 416/DIG. 3; 72/335
[58] **Field of Search** .... 29/156.8 B; 239/399, 239/406, 380, 383; 415/52; 72/335; 416/223 R, DIG. 3

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Pack, W. W.; Ivanov, S. K.; and Wereschtschagin, W. P.; Moskau 1974 (USSR Publishing House "Nedra") pp. 98–107.

Primary Examiner—Howard N. Goldberg
Assistant Examiner—Leonard S. Selman
Attorney, Agent, or Firm—Dann, Dorfman, Herrell and Skillman

[57] **ABSTRACT**

A guide vane ring for a return flow passage in axial fans comprises a ring (3) intended for placing in the return flow passage (4) coaxial with the impeller (6). A plurality of guide vanes (7) are formed integral with the ring and distributed round its exterior circumference. In a method of producing such a ring integral with its vanes, separate longitudinal slits are formed in a line one after the other in a metal strip. A cut is made transverse the strip between one end of each slit and one long edge of the strip. Portions of the band thus cut free are bent out from its plane and formed to a desired configuration, whereafter the formed band portions are bent such that the transverse cut lines will extend substantially at right-angles to the unformed flat band portion. This flat band portion is cut to desired length, formed and joined together into a circular ring with the portions formed to desired configuration forming exterior, substantially axially disposed guide vanes.

7 Claims, 7 Drawing Figures

Fan Case With Anti-Stall Ring

- In practice, the casing treatment comprises a set of static vanes, and a short casing segment under the vanes.
- As the fan approaches stall, flow is centrifuged up the blade towards the tip.
- As the fan stalls the flow reverses direction at the blade tip.
- The anti-stall ring provides the flow with an "escape route" turning the flow to the correct direction and re-introducing it into the casing upstream of the fan blades.

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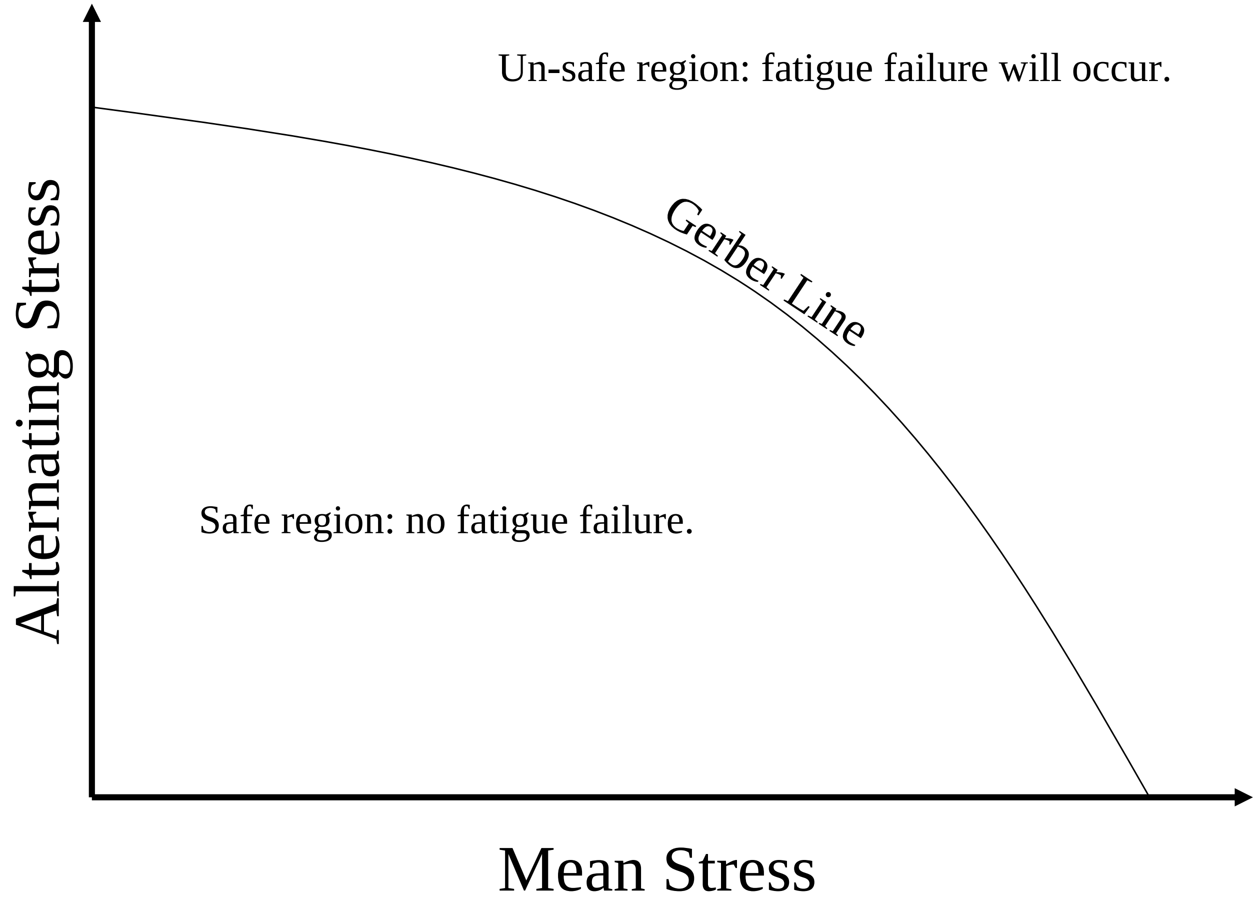
Fatigue Failure & Mechanical Design

- When a fan stalls the flow separates from the blades, resulting in turbulent flow though the blades.
- The turbulent flow buffets the fan blades, resulting in unsteady mechanical loads on the blades.
- The unsteady mechanical loads on the blades result in an alternating stress being induced in the blades.

Fatigue Failure & Mechanical Design

- Any material can withstand an ultimate load before it will break.
- If an alternating load is superimposed upon a steady load, the magnitude of steady load that can be tolerated without breaking is reduced.
- The relationship between steady and alternating load is known as the Gerber Line.

Fan Blade Failure in Fatigue



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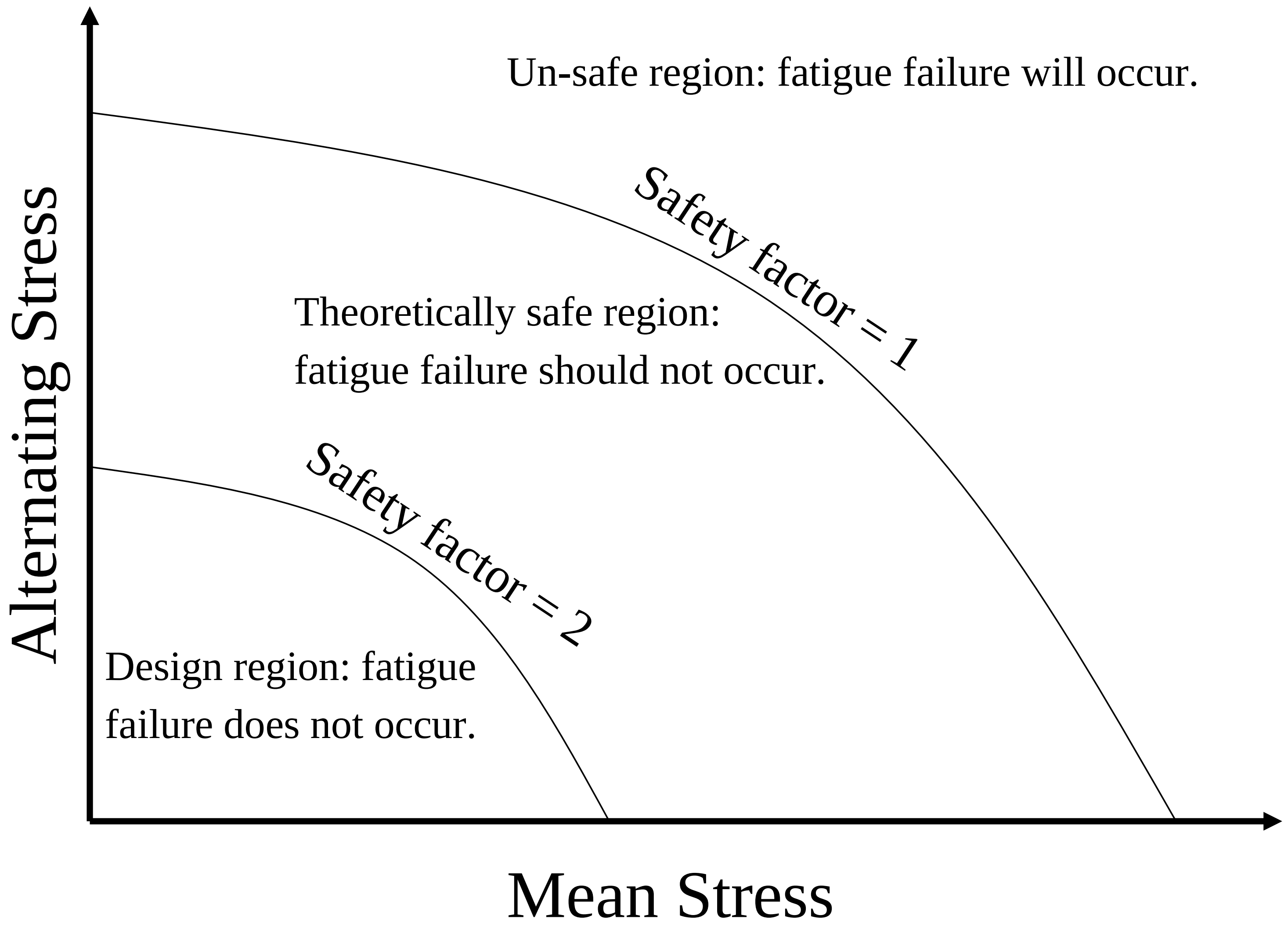
Safety Factors

- In practice, the location of the Gerber Line must be derived empirically.
- The derivation must be for a material with a known maximum defect size.
- In practice, fan designers typically use a safety factor of two to ensure that they do not inadvertently over-pass the Gerber Line.

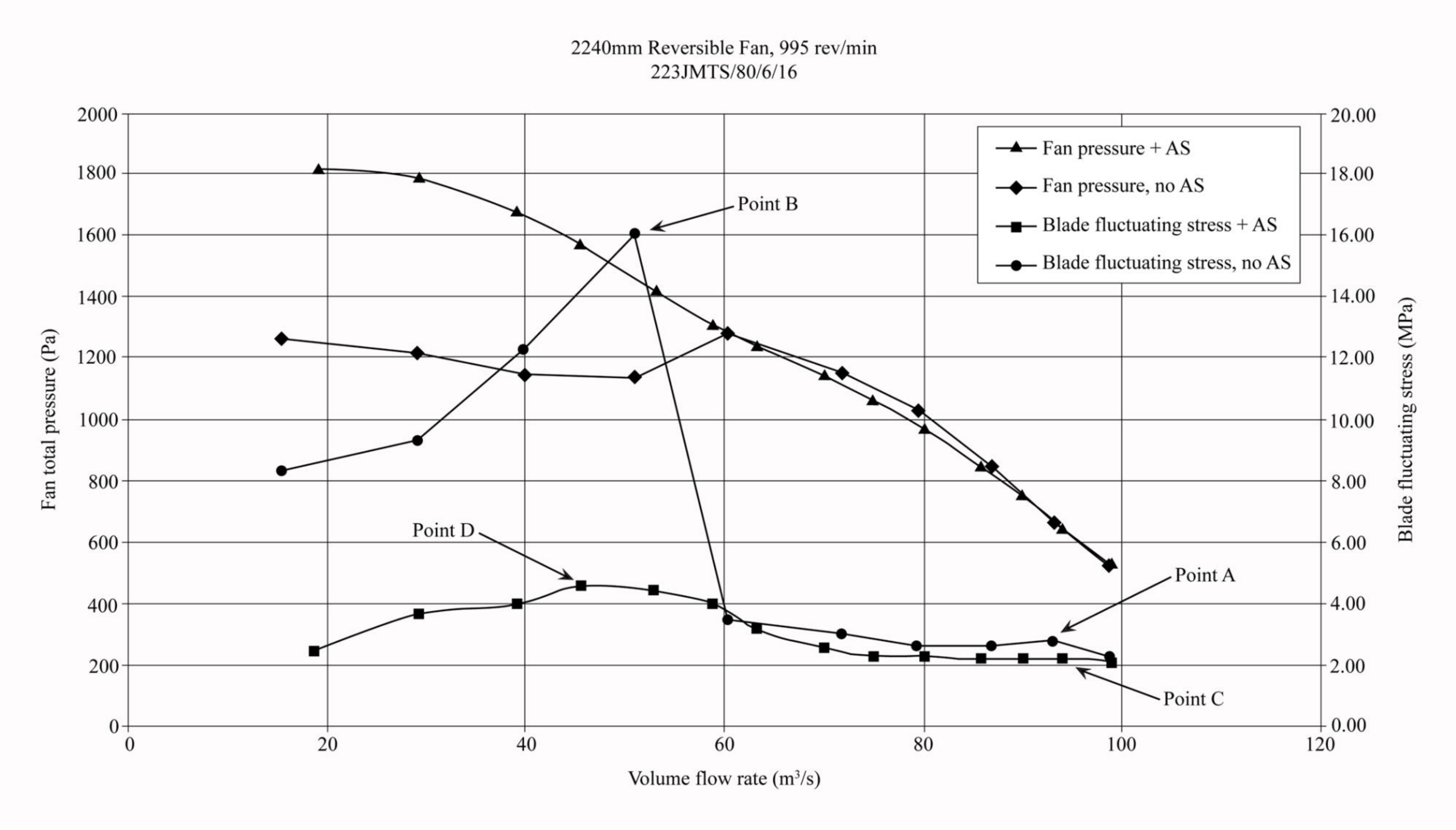
Safety Factors



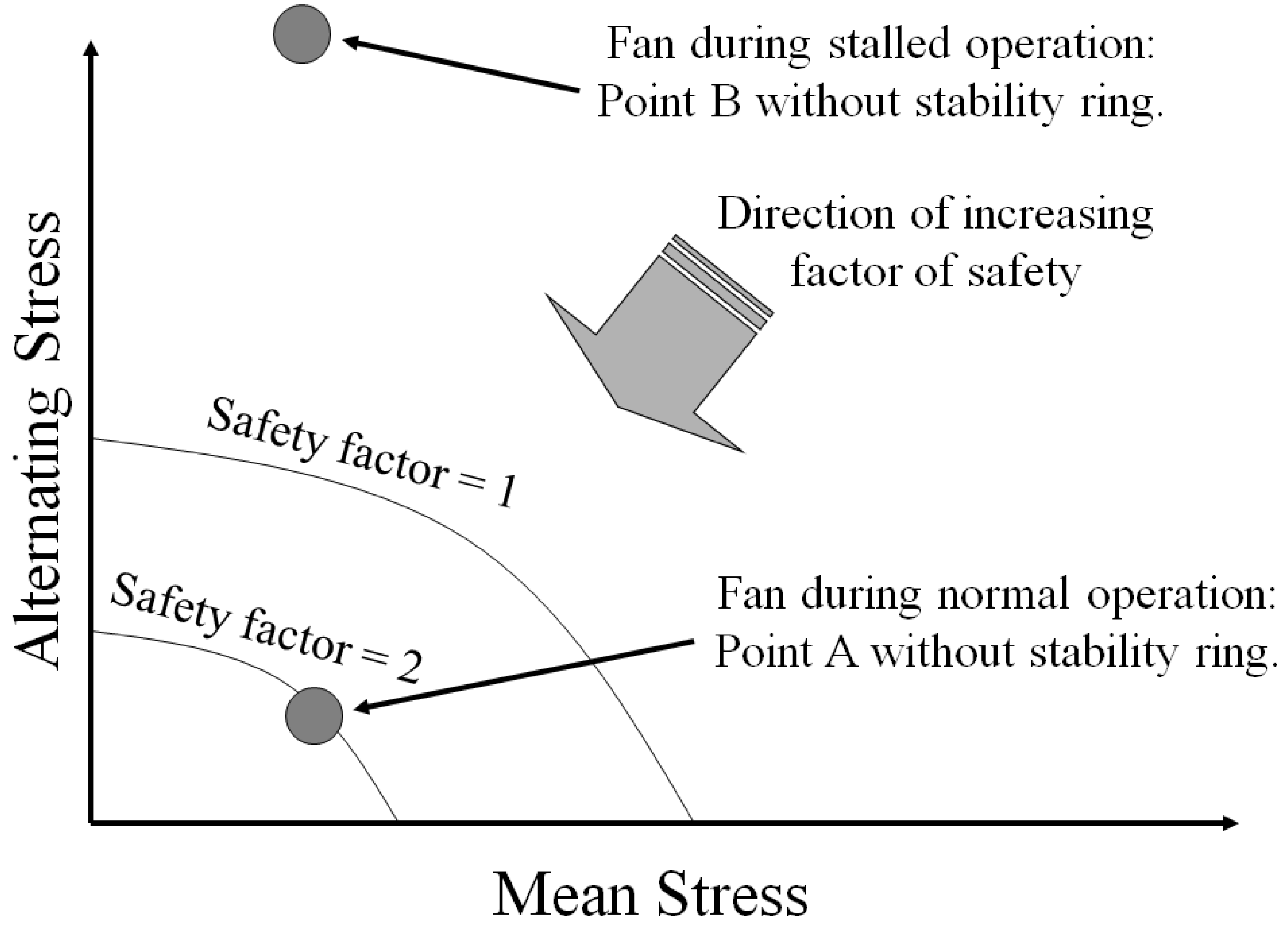
The Effect Of An Anti-Stall Ring

- First consider a fan with a plane casing.
- When a fan blade is fitted with strain gauges, the alternating stress can be measured when the fan is not stalling (Point A), and when it is stalling (Point B).
- The increase in alternating stress takes the fan blade into the unsafe region of the Gerber chart.

The Effect Of An Anti-Stall Ring

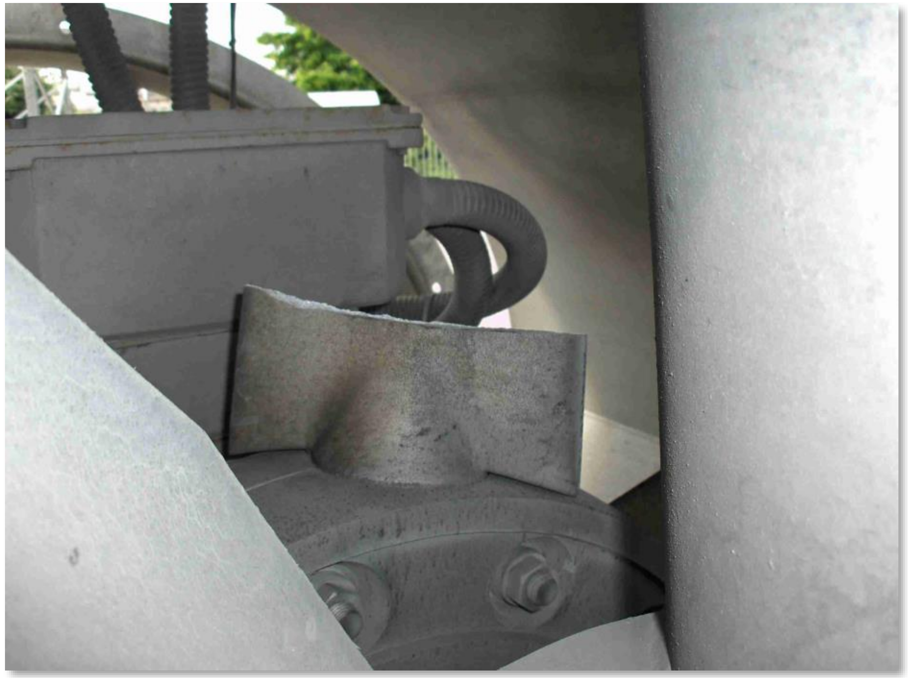


Impact on Mechanical Design: No Anti-Stall Device



What Happens At “Point B”?

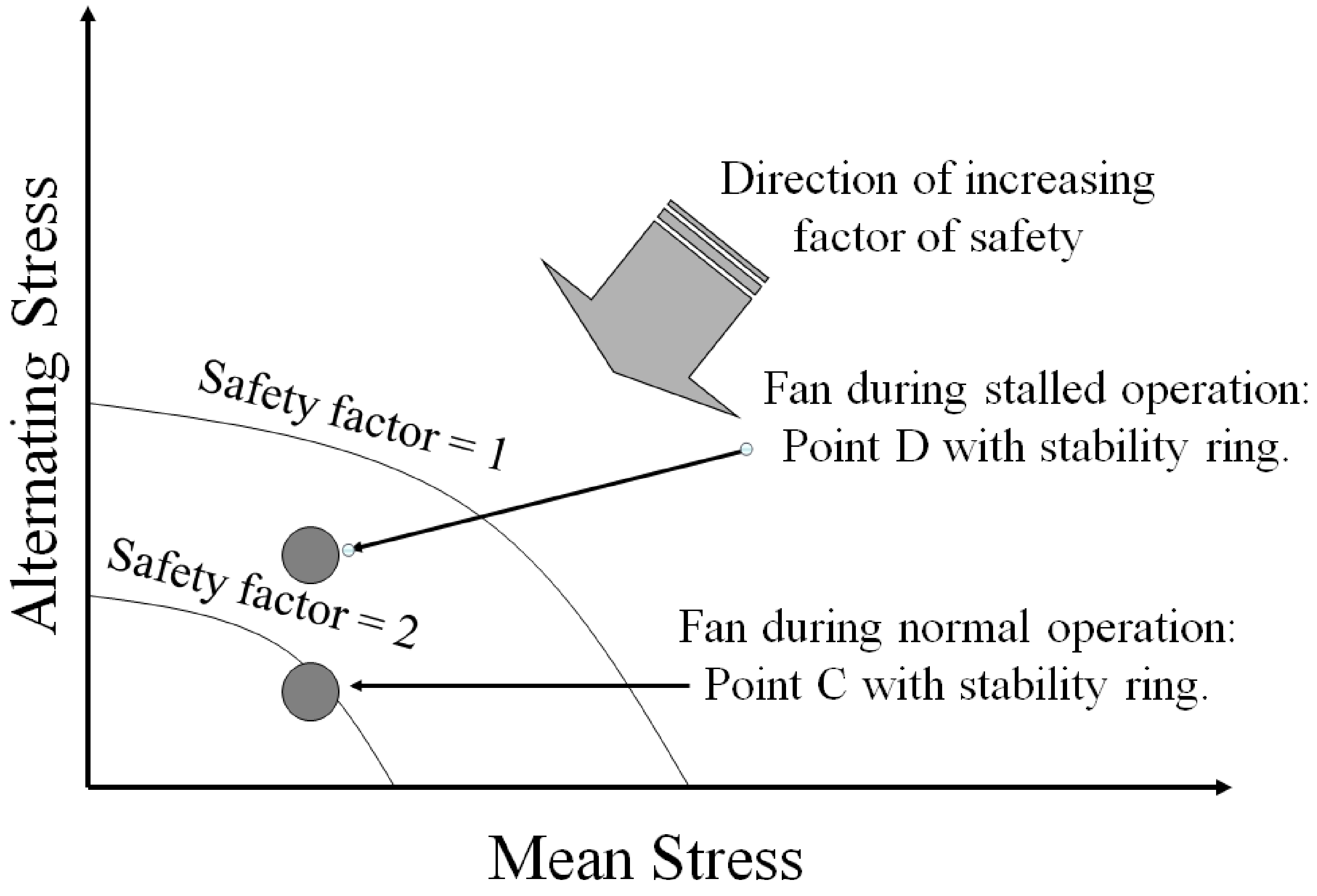
- When a fan operates in the unsafe region of the Gerber chart, then fan blades fail in fatigue.
- Fatigue is a failure mechanism associated with the repeated application of a mechanical load that does not immediately result in mechanical failure but will fail after a critical number of cycles.



The Effect Of An Anti-Stall Ring

- Now consider the same fan with an anti-stall ring fitted to the casing.
- When a fan blade is fitted with strain gauges, the alternating stress can be measured when the fan is not stalling (Point C), and when it is stalling (Point D).
- The alternating stress increases by a factor of 2.16, but this does not take the fan blade into the unsafe region of the Gerber chart.

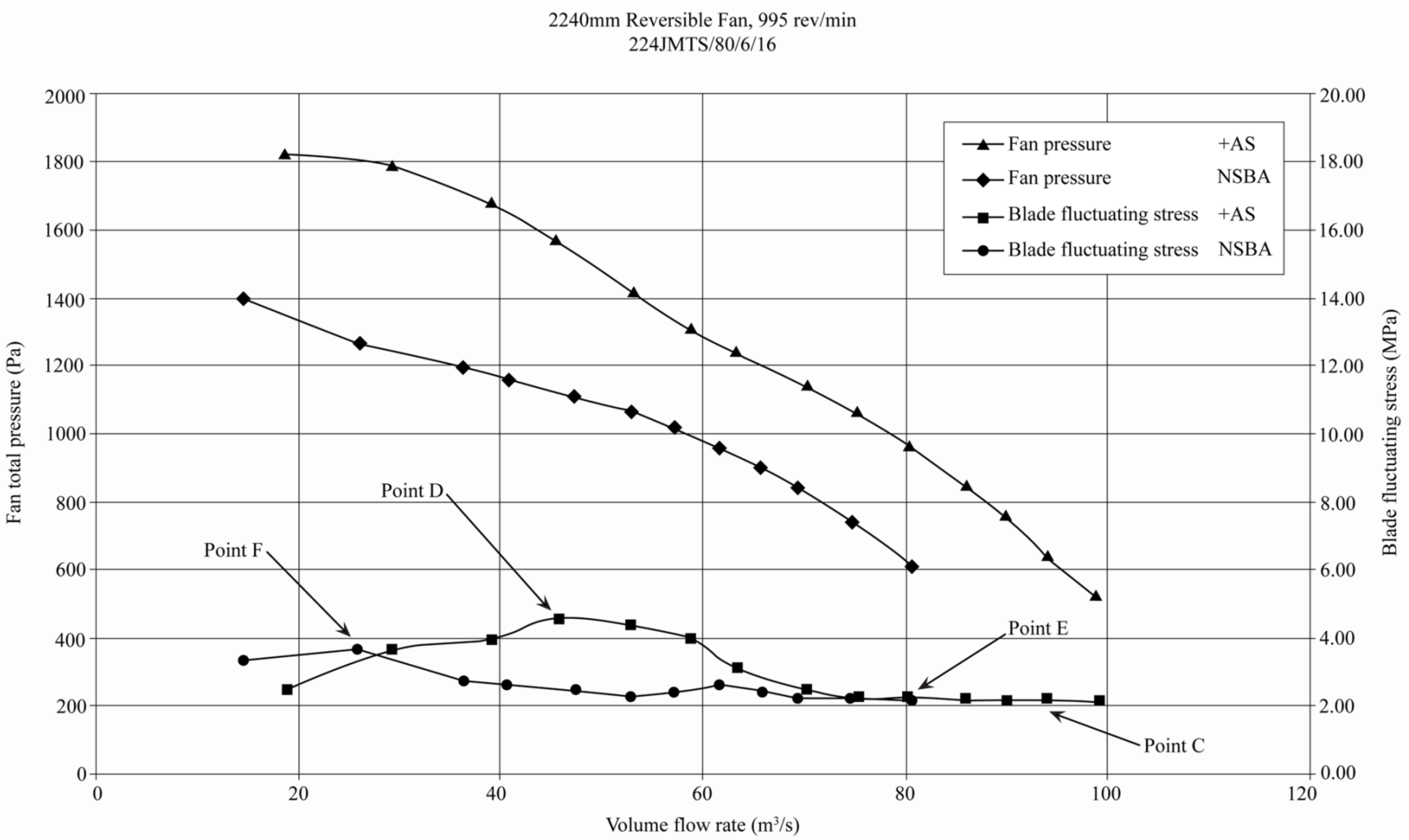
Impact on Mechanical Design: With Anti-Stall Device



The Effect Of A Non-Stalling Blade Angle

- For comparison, we now consider a fan with a non-stalling blade angle.
- When a fan blade is fitted with strain gauges, the alternating stress can be measured when the fan is not stalling (Point E), and when it is stalling (Point F).
- The increase in alternating stress is less then that for a fan with an anti-stall ring fitted (Points C & D).

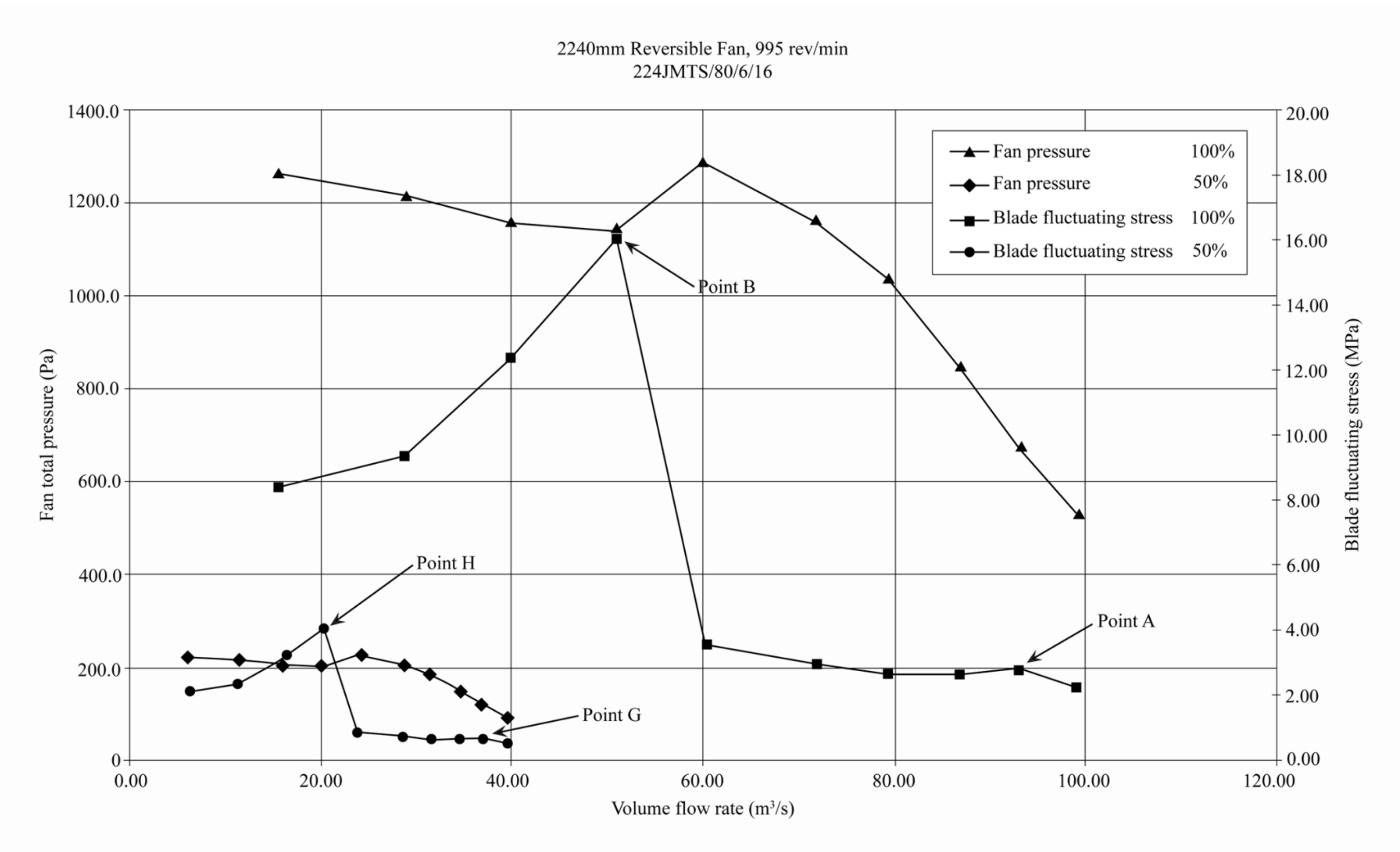
The Effect Of A Non Stalling Blade Angle



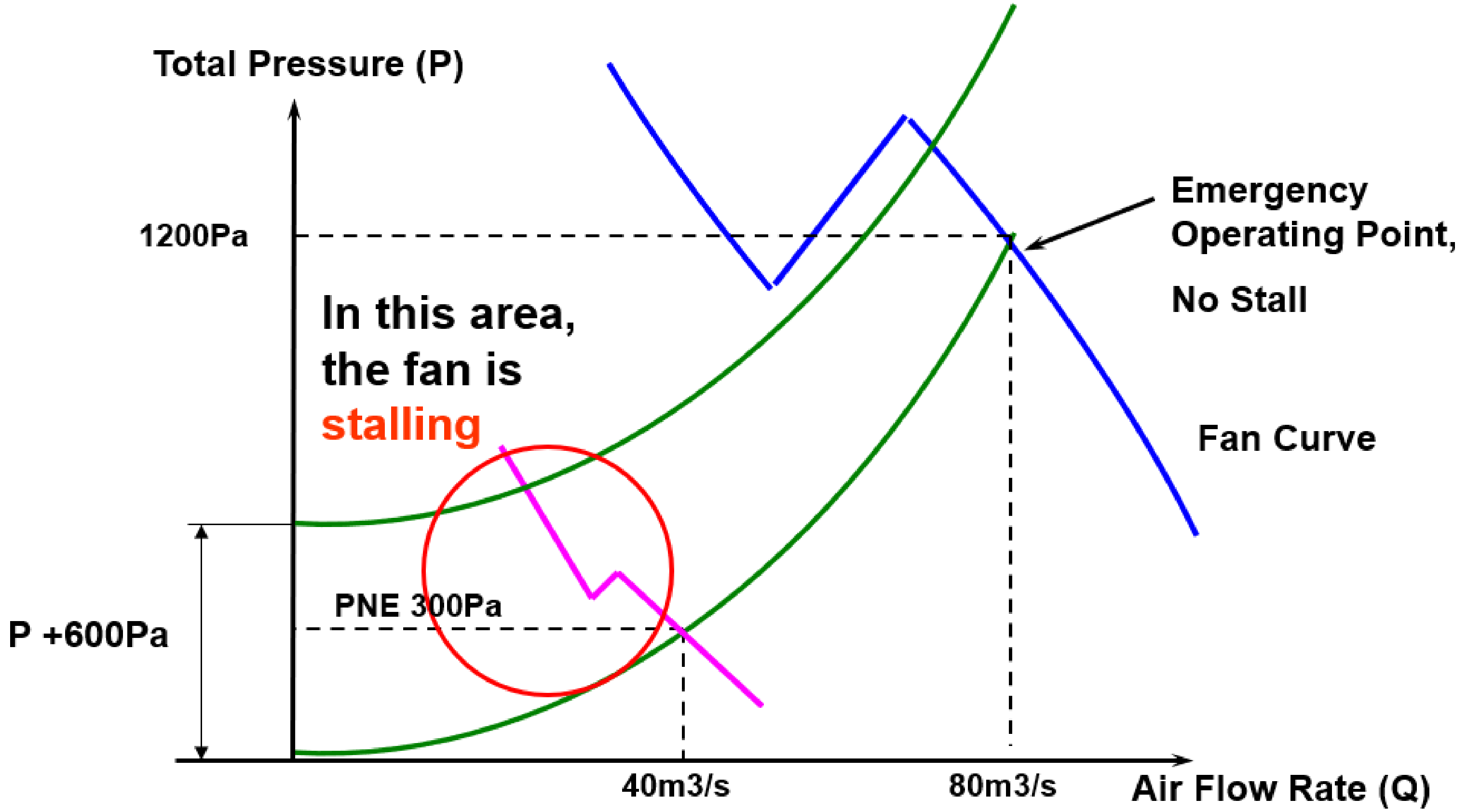
The Effect of Running at Half Speed

- When a fan operates at half speed, its pressure developing capability reduces.
- A fan that can accommodate a pressure pulse at full speed may stall when subjected to the same pressure pulse running at half speed.
- As a consequence of stalling at half speed, there is a risk that fans running at half speed may suffer a fatigue blade failure that would not occur if the fan was run at 100% speed.

Mechanical Effect of Half Speed



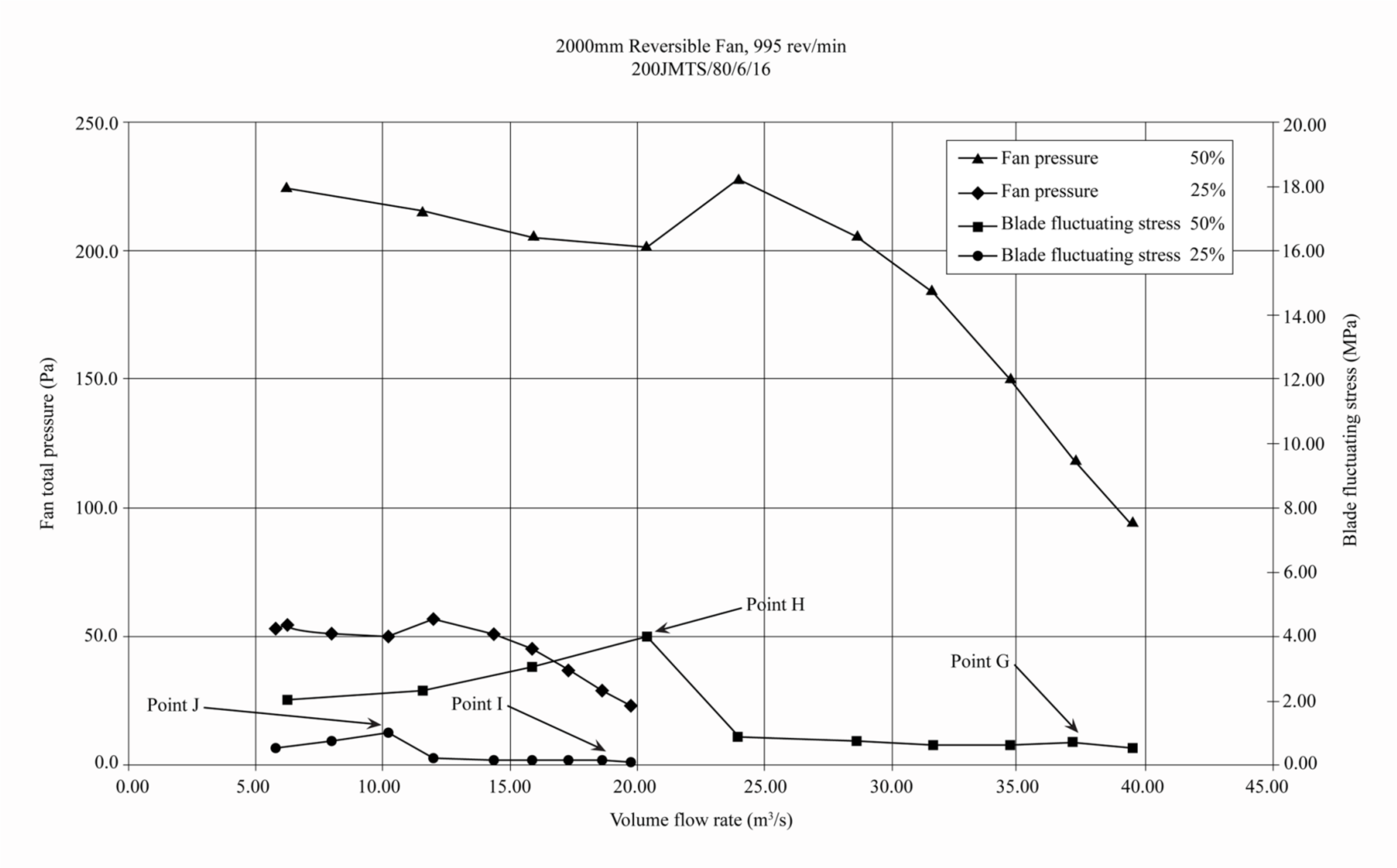
Aerodynamic Effect of Half Speed



The Effect of Running at Quarter Speed

- When a fan runs at quarter speed and is subjected to the same pressure pulse that could be accommodated at 100% speed, it not only stalls but is completely overwhelmed by the pressure pulse.
- Air can actually flow though the fan the wrong way during a transient stall at quarter speed.

The Effect of Running at Quarter Speed



Mechanical Safety Factors: Casing

- Mechanical safety factor may be defined as the depth into the safe region of the Gerber chart.
- When the strain gauge data in this presentation is analyzed, we see that a fan with a safety factor of 2.3 reduced to 0.3 in stall, and hence the fan blades break.
- The same fan with an anti-stall casing fitted has a safety factor of 2.5, reducing to 1.1 in stall. As 1.1 is greater than 1.0, the fan blades should not suffer a fatigue failure.
- A fan with a non-stalling blade angle has a safety factor of 2.4, reducing to 1.5 in stall. As it has the largest safety factor in stall it is the lowest risk selection.

Mechanical Safety Factors: Casing

Fan Type	% Full Speed	Normal operation safety factor	Stalled operation safety factor
Plane casing, stalling blade angle	100	2.3	0.3
Anti-stall casing, stalling blade angle	100	2.5	1.1
Plane casing, non-stalling blade angle	100	2.4	1.5

Safety factor derived from strain gauge data for a fan at full speed.

Mechanical Safety Factors: Speed

- If we now consider a fan with a plane casing, we know that it has a safety factor of 2.3, reducing to 0.3 when stalling.
- When running at 50% speed the same fan has a safety factor of 10.0 reducing to 2.5 when stalling.
- As 2.5 is larger than 2.3, we may conclude that this fan is safer when operated at 50% speed in stall then it is under normal operation at 100% speed. Consequently, we can conclude that this fan is safe to run at 50% speed in the presence of pressure pulses that will cause it to stall.
- At 25% speed, safety factors are large as a consequence of the low direct stress, and so the fans are safe to run in stall at 25% speed.

Mechanical Safety Factors: Speed

Fan Type	% Full Speed	Normal operation safety factor	Stalled operation safety factor
Plane casing, stalling blade angle	100	2.3	0.3
Anti-stall casing, stalling blade angle	50	10.0	2.5
Plane casing, non-stalling blade angle	25	106.0	7.3

Safety factor derived from strain gauge data for a fan at full- and part-speed with and without a fitted stabilization ring.

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Fan Duty Point & Costs

- The relative merit of the three selection strategies may be illustrated by picking a typical duty point, operating time and costs.
- This analysis is intended to provide an economic bench-mark to enable the relative merits of the three selections strategies to be assessed.

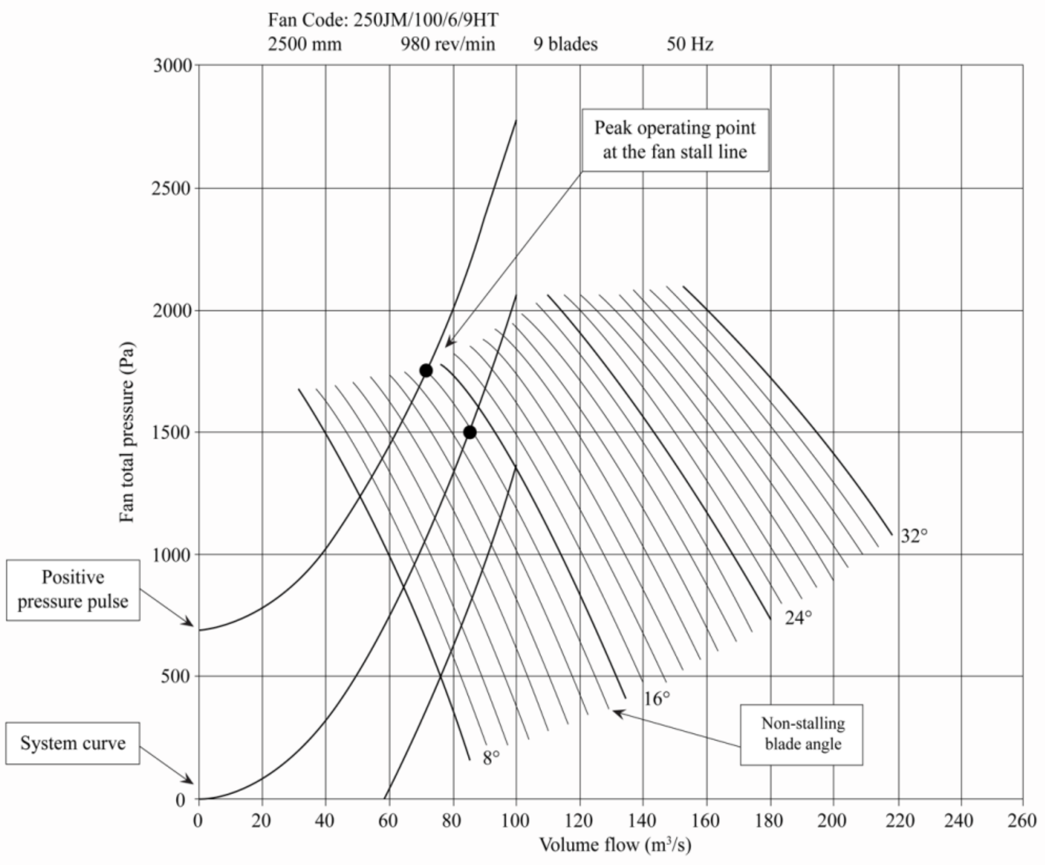
Fan Duty Point & Costs

Design Point Pressure	1,500 Pa
Pressure Pulse	500 Pa
Design Point Flow	85 m^3/s
Fan Type	Reversible, 300 ^0C for 2 hours
Running hours per year	4,400 (12 hours a day)
Cost of electricity	0.04 £ per kW/Hour
Cost of capital	8%
Period of assessment	10 years

Factors impacting on fan capital and through life cost.

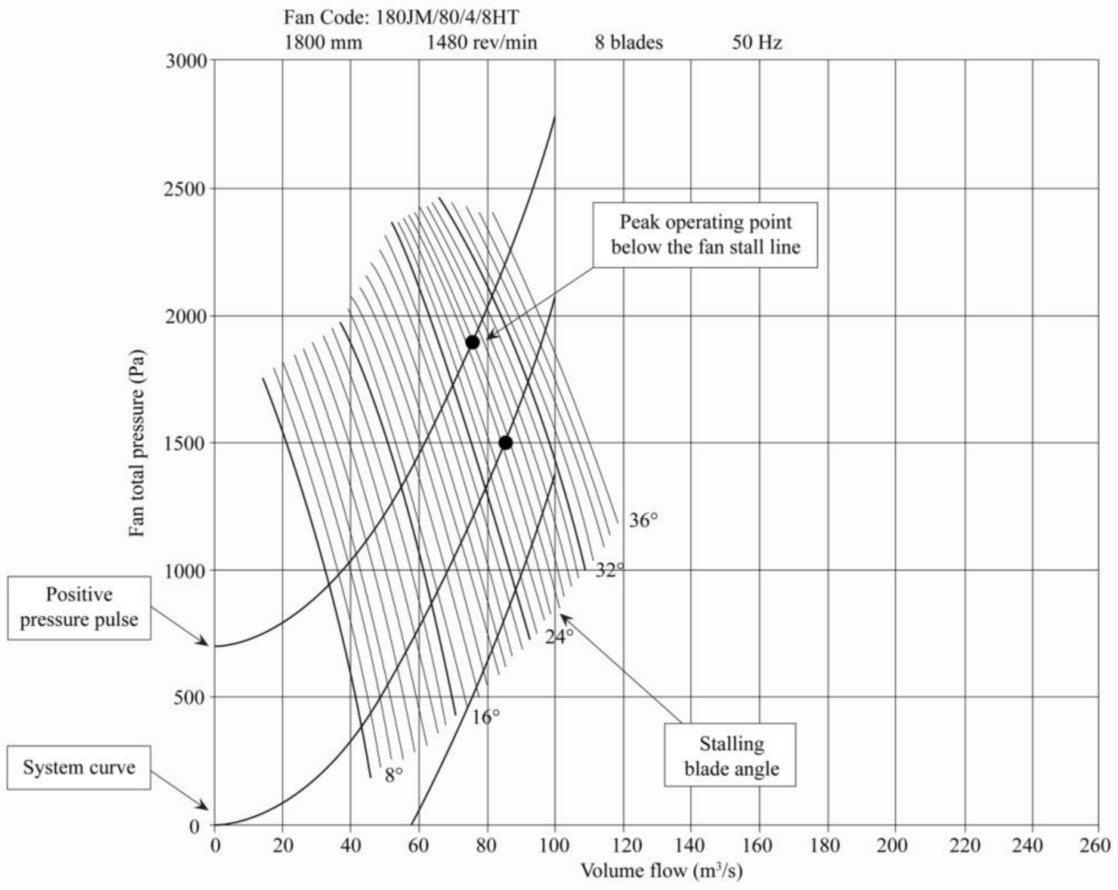
Selection Strategy 1: Non-Stalling Blade Angle

- For the duty point, a selection with a non-stalling blade angle results in a 2.5-meter diameter fan running at 6-Pole speed.
- In this example, the fan characteristics back to zero flow are not published, as it is considered bad practice to select a fan at these high-pressure low flow points on the fan chart.



Selection Strategy 2: High Pressure Development Capability

- For the duty point, a selection with a stalling blade angle results in a 1.8-meter diameter fan running at 4-Pole speed.
- The increase in speed compared to the non-stalling fan results in a higher-pressure developing capability, and consequently the pressure pulse can be accommodated within the fan chart without the risk of the fan stalling.

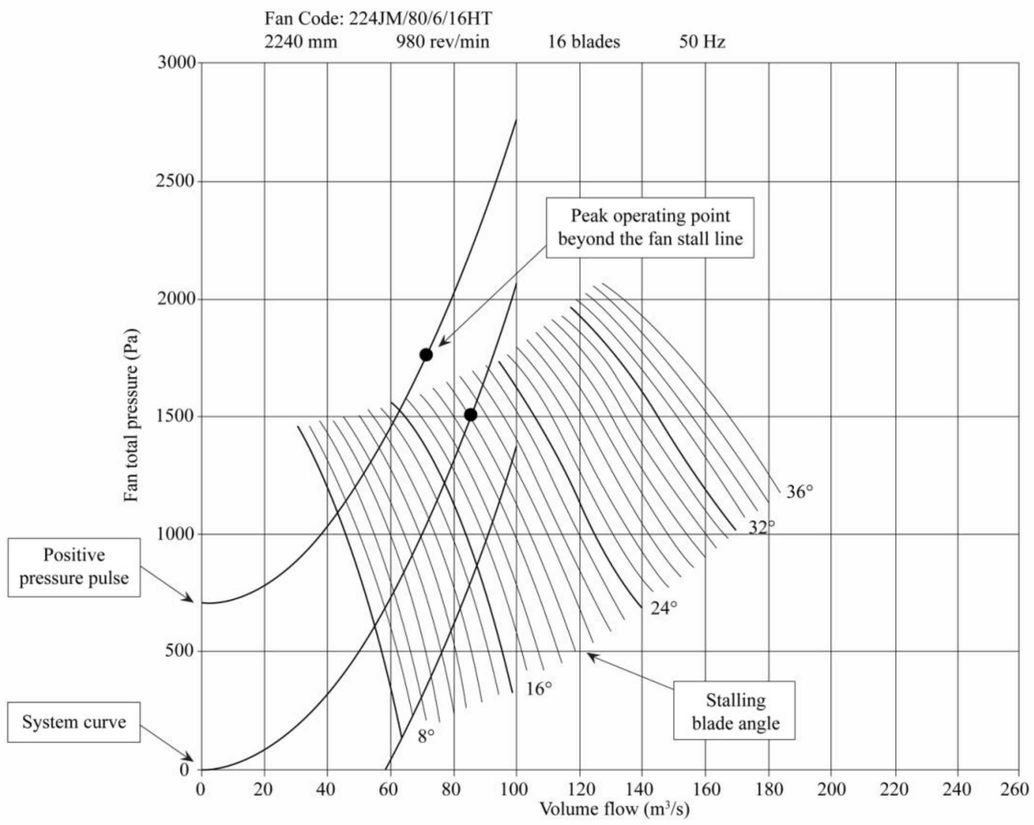


Selection Strategy 3: Anti-Stall Ring

- For the duty point, a selection with a stalling blade angle and an anti-stall ring fitted to the casing results in a 2.24-meter diameter fan running at 6-Pole speed.

- In this example, the duty point has been selected at a point as close to the fan stall line as good practice allows, with the duty point in the stalled area when the fan is subject to a pressure pulse.

- The assumption is that during a pressure pulses the anti-stall ring will mechanically protect the fan from the effects of aerodynamic stall.



Capital & Through Life Cost

- Each fan selection results in a different fan, with a different duty point efficiency and capital cost.
- When the fan efficiency is used to calculate the cost of electricity per year and combined with the capital cost of the fan, then the total cost of ownership of the fan over ten years can be calculated.
- When capital cost and total cost of ownership are studied, we see that the lowest cost fan to buy (the 1.8-meter fan associated with selection strategy 2) is also the most expensive to own.
- The fan with the non-stalling blade angle is the lowest cost to own over ten years but is also the largest and therefore requires the largest (and hence most expensive) plant room.

Capital & Through Life Cost

	Fan Diameter ***(m)***	***Fan Efficiency***	***Fan investment cost*** ***(£)***	***Motor power*** ***(kW)***	***Electricity cost/year*** ***(£)***	***Electricity cost (10 yrs)*** ***(£)***	***Total Fan and running costs*** ***(£)***	***Running cost as a percentage of total cost***
Strategy 1	2.5	71%	28,500	185	32,412	217,488	245,988	88%
Strategy 2	1.8	66%	23,000	214	37,493	251,582	274,982	92%
Strategy 3	2.24	69%	32,000	190	33,288	223,366	255,366	87%

Capital cost and ten year though life cost of each selection strategy.

Agenda

- Aerodynamic Stall
- Pressure Pulses
- Solutions to Accommodate Pressure Pulses
    - Selection Strategy 1
    - Selection Strategy 2
    - Selection Strategy 3
- Anti-Stall Casing Treatment
- Mechanical Failure Mechanism
- Safety Factors
- Example Practical Selection & Cost Implications
- Conclusions & Supplementary Material

Conclusions

- Three selection strategies have been presented, all three of which are in routine and reliable operation in metro systems around the world.
- There is no “correct” approach to the avoidance of fan aerodynamic stall; however, the anti-stall ring has become a popular choice in some global regions.
- An anti-stall ring does reduce the mechanical impact of a fan driving into stall but does not eliminate the impact.
- Alternating stress level in the fan tested increased by a factor of 2.16 when the fan studied was driven into stall with an anti-stall device fitted.

Conclusions

- If the fan is to operate reliably, the mechanical design must account for the increase in alternating stress when the fan stalls; not doing so could result in the fan's fatigue related mechanical failure.
- There have been in-service failures of fans fitted with anti-stall rings, and it is suspected that the design engineer responsible assumed that the anti-stall ring provided complete mechanical protection – which it does not.
- When accounting for the increase in alternating stress when a fan stalls, the fan designer makes assumptions about the maximum defect size in the fan blades and hub.
- The 100% X-Ray inspection of all rotating parts is essential to verify that the fan designers' assumptions regarding maximum defect size are not exceeded.

Supplemental Material

The material contained within this presentation is the subject of a technical paper:

- **Sheard, A.G. & Corsini, A. (2012)**, ‘The Mechanical Impact of Aerodynamic Stall on Tunnel Ventilation Fans’. *International Journal of Rotating Machinery*, vol. 2012, Paper No. 402763, pp 1–12.

The paper can be downloaded free of charge using the link:
http://www.hindawi.com/journals/ijrm/2012/402763/

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Research Article

The Mechanical Impact of Aerodynamic Stall on Tunnel Ventilation Fans

A. G. Sheard[1] and A. Corsini[2]

[1] *Flākt Woods Ltd., Axial Way, Colchester CO4 5ZD, UK*
[2] *Dipartimento di Ingegneria Meccanica e Aerospaziale, Sapienza University of Rome, Via Eudossiana 18, Rome 00184, Italy*

Correspondence should be addressed to A. G. Sheard, geoff.sheard@flaktwoods.com

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This paper describes work aimed at establishing the ability of a tunnel ventilation fan to operate without risk of mechanical failure in the event of aerodynamic stall. The research establishes the aerodynamic characteristics of a typical tunnel ventilation fan when operated in both stable and stalled aerodynamic conditions, with and without an anti-stall stabilisation ring, with and without a “nonstalling” blade angle and at full, half, and one quarter design speed. It also measures the fan’s peak stress, thus facilitating an analysis of the implications of the experimental results for mechanical design methodology. The paper concludes by presenting three different strategies for tunnel ventilation fan selection in applications where the selected fan will most likely stall. The first strategy selects a fan with a low-blade angle that is nonstalling. The second strategy selects a fan with a high-pressure developing capability. The third strategy selects a fan with a fitted stabilisation ring. Tunnel ventilation system designers each have their favoured fan selection strategy. However, all three strategies can produce system designs within which a tunnel ventilation fan performs reliably in-service. The paper considers the advantages and disadvantages of each selection strategy and considered the strengths and weaknesses of each.

1. Introduction

The operating maps of fans and compressors are limited by the occurrence of aerodynamic instabilities when throttling the flow rate. Aerodynamic flow instabilities place considerable mechanical stress on the rotors, which can eventually lead to mechanical failure. Rippl [1] conducted strain gauge measurements on axial compressors, concluding that alternating stress in vanes exceeding stable operation by a factor of five under “rotating stall” conditions. This leads to rapid fatigue failure of the blades. In contrast, a “surge” can lead to the heightening magnitude of bending stress enough to cause a mechanical failure during the surge event itself.

Fan designers classically produce a mechanical design that can withstand the alternating loads imposed on the fan blades associated with rotating stall, and therefore mechanical failure during a stall event is not instantaneous. Aluminium is both low cost and light weight, and consequently the fan designers’ preferred choice of blade material. A weakness of aluminium as a structural material is its propensity to fail in fatigue. As such, fan blades that do not typically instantaneously fail during rotating stall fail in fatigue sometime later. The latter failure occurs as a consequence of a fatigue-induced crack initiated in a blade as a consequence of the higher stress during the rotating stall that then goes on to propagate during stable operation.

This paper studies the impact of rotating stall, generally referred to as “aerodynamic stall” within the fan industry, on the mechanical performance of a typical tunnel ventilation fan. The paper starts with a brief literature review relating to fan, blower, and compressor aerodynamic stall before moving on to review the antistall concepts that other scholars have developed in their attempts to improve axial decelerating turbomachinery aerodynamic stability. Placing strain gauges in the location of the fan blades’ peak stress, the authors were able to establish the mechanical impact of aerodynamic stall with and without an antistall stabilisation

Resources

- **AMCA International**: *www.amca.org*
- **AMCA Publication:** *www.amca.org/store*

  > **202-17**: Troubleshooting (Available for purchase)

- **ANSI/AMCA Standard:** *www.amca.org/store*

  > **250-12**: Laboratory Methods of Testing Jet Tunnel Fans for Performance (Available for purchase)

Questions?

Thank you for your time!

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Review Questions

- *Question 1: What is aerodynamic stall?*
- *Question 2: Can you name two strategies for avoiding stall when selecting a fan?*
- *Question 3: When a fan stalls, why do fan blades fail mechanically?*
- *Question 4: When assessing a fans mechanical design, what would be an acceptable mechanical safety factor?*
- *Question 5: If you want to minimize technical risk when selecting a tunnel ventilation fan, what type of fan should you specify?*