# DAMAGE MECHANISMS INVOLVING SEALS AND SECONDARY FLOWS: THE POTENTIAL FOR BENEFICIAL APPLICATION OF PROBABILISTIC METHODS

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I'm going to talk about damage mechanisms and ways we might beneficially apply probabilistic methods. Why do I think we might get some benefit? Well, modeling methods, measurements, and criteria are all subject to uncertainty. Probabilistic methods give us a way of managing uncertainty. They provide a new framework for engineering analysis and recommendations. They support and enhance economic decision analysis, and they are currently underutilized. I'm coming at this particularly from the industrial turbomachinery point of view. I deal a lot with people who have to run plants to make product and make a profit doing it. They want to put in reliable, robust, machinery if it's new, but they also have a big problem running a huge installed base of old stuff that they have to maintain and operate. That's a big part of any plant's concerns. So there are two points of view: 1) making new plant reliable, and 2) operating old plant reliably. In twenty minutes I'm going to touch some high spots and hope that maybe I stimulate some ideas. Some damage mechanisms I'll talk about are seal rubs, diffuser stall in centrifugal compressors, turbine blade failure due to forced vibration, compressor blade failure due to material imperfections, and consequential damage from tip rubs. I'll talk first about something that relates back in a way to what Joe Kulesa from GE was talking about. This is an example in a petrochemical plant of a seal rub. It's actually called the Newkirk effect: as the rotor rubs due to vibration, it preferentially heats that rotor on one side, causes its unbalance to change, and the vibration changes as a result. If running below critical speed, it tends to "grow into" that critical speed and vibrations get worse. If you're above that critical speed, the vibrations decay. This figure shows slow acceleration towards a critical speed. And you can see the vibration amplitude of the rubs getting higher up to this point and then they backed off in the speed and vibrations started coming down. This is a steam turbine in a petrochemical plant, and these are a benign kind of rub. It's a flexible seal or packing that's actually spring loaded in position. It rubs the seal, moves out of the way, but it still causes some damage <u>and</u> heats the rotor.

Another problem that's really widespread is diffuser rotating stall and I'll show a couple of examples.

This slide shows vibrations on a 20,000 RPM centrifugal compressor. This has the one per rev vibration at running speed and this nasty little peak back here at just around 10% of running speed. That frequency is a characteristic of stall in the diffuser, and it's a very high vibration, 2 mils on a 20,000 RPM machine is really very high. This is a problem that turns out to be very difficult to manage in high performance, low flow, high pressure turbomachinery.

This slide shows an example of another problem from a power plant. You can see the scale, it's a man standing there. This slide shows consequential damage from tip rubs due to thermal distortion of the casing. The tip rubs in themselves did not cause immediate failure, but eventually they caused a blade to break loose and become a missile within the turbine and cause this damage. So, of course that's very upsetting if you're operating the turbine! Predicting seal rubs, either at the design stage or if you're making measurements and you want to know whether you're likely to have a seal rub is difficult, and this amplifies the problem. This slide shows a schematic of a rotor that's vibrating in its bearings, the bearings are at the end, and that's the seal rub location in the middle. You have various contributory deformations; there's a vibration deformation; and there's a shaft bending deformation; and there's deflection of the shaft within the bearings. These are all uncertain things. You can make measurements at the bearing - eddy current problems will give you a good measurement of the shaft position and vibration, but what's happening at the seal is a difficult question. Maybe this slide makes the dilemma clearer. We've got a nominal seal clearance. We've got a measurable eccentricity vector - the midpoint or average position of the shaft. We've got measurable vibration here, this small ellipse. But the things we can't measure are how much the shaft further deflects as it bends towards the middle of the shaft, and what the mode shape does to the vibration at the mid spin. So you have to make inferences through models and could eventually infer the seal rub margin, but all these things are subject to uncertainty. And this next slide summarizes some of the contributory uncertainties. We don't know the shaft position exactly. We could measure it with some variance, and vibration is subject to variance. The vibration multiplier of the seal and the seal clearance itself are also subject to uncertainty. So I list here possible coefficients of variance on the first four parameters which gets you to the probability of seal rub. There are certain other parameters which represent "so what." How much will the clearance increase as we rub, what is the risk of a catastrophic failure, and what's the dependence of efficiency loss? These consequential questions are subject to uncertainty. Applying probabilistic methods to a model - this is an example of predicting probability of failure. This shows probability of a seal rub as a function of vibration amplitude for two different clearances. This sort of calculation can be used in a design mode: What clearance do I want to set on this seal for the sort of vibration I might expect? Alternatively, if the machine is installed and running with some vibration, what's the probability that the vibration is going to cause a seal rub? So probabilistic methods can help both design and operational questions.

I want to give some strong credit to NASA at this point for the development of probabilistic methods and for focusing on this problem. The NESSUS code (which stands for Numerical Evaluation of Stochastic Structures Under Stress) was championed by Chris Chamis, and the work was done at Southwest Research Institute. It's a system for managing uncertainty through various probabilistic analysis methods. In essence what it does, it allows you to map from input distributions on tolerances, material properties, service requirements, loads, damping, etc. through a complex model, to an output which is a distribution of performance or failure probability. It uses advanced methods because if you think of running an FEM analysis which takes five minutes every time you do it and you want to get 5-9's reliability, probabilistic analysis will say you've got to make about a million simulations using Monte Carlo methods, so you're in for a long wait for the answer. But there are some advanced methods that allow you many orders of magnitude reduction in those times and those are integrated into the NESSUS code. During the NESSUS development program, there was some verification not just on natural frequencies, but on actual prediction of the variance of natural frequencies. This is an SSME turbo pump blade and we use NESSUS to predict coefficient of variance. Those are the green lines, these are frequencies. By testing about 100 blades, they were able to measure the coefficient of variance. And you can see that with the input uncertainty, it was possible with reasonable confidence to predict what the coefficient of variance would be.

I'm pleased to see that probabilistic methods are slowly getting transferred into applied technology. This is a recent example of a paper on a steam turbine. This is by Tony Lam at Stress Technology. It illustrates a way of presenting probabilistic information. The paper addresses the question "Could the vibration stress exceed the high cycle fatigue limit?" And so here is the fatigue limit. And each point on the figure is a Monte Carlo simulation for stress. Each point above the line would be a failure. What they're actually trying to do here is a postdictive analysis, to try and explain an observed failure. So you can see here how it works out. The majority of the simulations are well below failure, but you get the occasional one that exceeds the line. This makes clear why mean value analysis isn't necessarily the total picture in design. You've got to design for the outliers as well to really build robustness into design. There's a program just starting at Southwest Research Institute now funded by the Federal Aviation Administration. The program team includes: Allied Signal, Allison, GE, Pratt & Whitney. Southwest Research is leading the program and it's to transfer probabilistic technology into the practice of these engine suppliers. The goal is to improve the safety of commercial airliner fleets by developing a generic, probabilistic based, damage tolerance design code for gas turbine rotors. The specific initial payoff is to reduce the occurrence of uncontained disc failures due to titanium manufacturing flaws (measured over a five year period at $1.4*10^{-8}$ per engine cycle). The goal is a significant reduction in that rate by developing and transferring into practice a probabilistic rotor design tool that takes into account manufacturing uncertainties.

Some other decisions that are potentially enhanced by probabilistic or economic analysis are rotor bearing design, deciding whether to shut down a machine that's making money for you, deciding whether or not to start a turbine based on its slow roll run out, and choosing inspection intervals. These are all effectively analyzed using probabilistic methods and can help economic based decisions. I'll talk about just a couple very quickly. Vibration criteria, why do we need a new approach? Well, operators run machines to make product and profit. If they shut down to balance, align, or correct a problem, that costs product and costs revenue. But of course running with excessive vibration carries a risk of catastrophic failure. So you've go two competing cost streams to balance. We need economically meaningful ways to measure when we reach excessive vibration. Quantify the risk and optimize the benefits. This machine is simply an asset. It's got to compete with making money in credit cards. A business can't afford to shut down just because an engineer says "you really need to shut down this machine or it's going to hurt itself." It's necessary to look at the "so what," which is economics. We're trying to promote a way of thinking about these questions based on the net present value of a decision. This flow chart gets us (in the end) to net present value, while looking at a decision "run it as is" or "take maintenance action?" Here are the two competing cost streams, first the expected consequential cost avoided. If I shut down because I might fail this rotor, I'm avoiding a consequential cost (a benefit). Secondly, there's a cost I immediately incur because I stop making money with that machine. You then have to provide inputs to these nodes. This tricky item - the probability of failure - is where the engineering skill comes in. I'm talking about a rotor dynamics model here, but there really may be a number of different models. You've got material properties, you've got measurements, and these all factor into the probability. Sometimes you can't make measurements. As Chris Chamis said, "Gut feel is an excellent input." Ask the operator of a machine what's the probability of failure of this machine? He could probably give a better answer in many cases than models can. If you ask him the right questions and lead him through, he's been sensing and integrating. He knows that machine. So, sometimes interview techniques supplement the engineering analysis. We have other known things including how much it's going to cost to shut down and fix that machine. And you eventually seek to choose a decision or course of action which optimizes the benefit. It may be to run the machine. If you're making money with it, it may be better to just go on running even though you have a high probability of damage. We just recently studied for some large power generating turbines, the net present value (NPV) to shut down and correct high vibration. In these examples, because we were looking at fairly severe vibrations the NPV always turned out to be positive, but in other circumstances it will be a different decision.

I talked about diffuser stall and I showed you how severe it can be, but it has many uncertainties. One is the operating envelope over which you're actually going to run the compressor; and what are the local geometry tolerances, what are the gas properties? How is the diffuser flow influenced by geometry, sped, gas flow, and properties? A very important parameter in diffuser stall is the angle at which flow comes into the diffuser. You've got the option to put a shunt between your discharge pressure and the seal, which can influence the flow and reduce the likelihood of stall. Many compressors survive some level of stall vibration, So you can look at consequences, what is the magnitude, frequency, or location of excitation if stall occurs, and what is the vibration sensitivity? This is some data that we took on a machine in two conditions. We're using Van Den Braembussche's diffuser stall criteria (he worked at the Von Karman Institute). This is a criteria for diffuser inlet flow angle. And in one case where the criterion said "unstable," the vibrations were high and there was observably flow instability; in another case, the results did not confirm the criterion. We reduced diffuser width from .03 to .02. This made it stable and measured data under two conditions confirmed the criteria. But overall, the observations show scatter and uncertainty; it's not precise science. Here's an outline of an approach to handle the uncertainty. We can create probabilistic distribution for the operating envelope, tolerances, gas properties, the rotor material properties. We can estimate model uncertainties either with intuition, test data scatter, or tolerances. We can put uncertainty into all these and then we can use Monte Carlo simulation, NESSUS advanced probabilistic approaches can then base a decision on what is the probability, what is the cost, and what is the consequences of a problem. You may be able to live with a problem if you're only going to have to run it under that condition for , say 5% of its life.

So I'd like to summarize. Probabilistic methods are underutilized, however, they provide a new framework for quantitative decision analysis, and they dovetail with economic analysis. Some of the promising fields, rotor dynamic design, vibration severity and shutdown management for seal and tip rubs, bearing fatigue (and bearing fatigue has a whole lot of interesting aspects to it), stall management, and generally robust design. Design to make the distributions narrow, don't just design for the main point. Thank you very much.

## QUESTIONS

**Q.** When in the NESSUS approach, in utilizing the models, like for example with FEM where you have nonlinearities, would it be better to employ linear perturbations, to not have to go through the immense number of calculations?

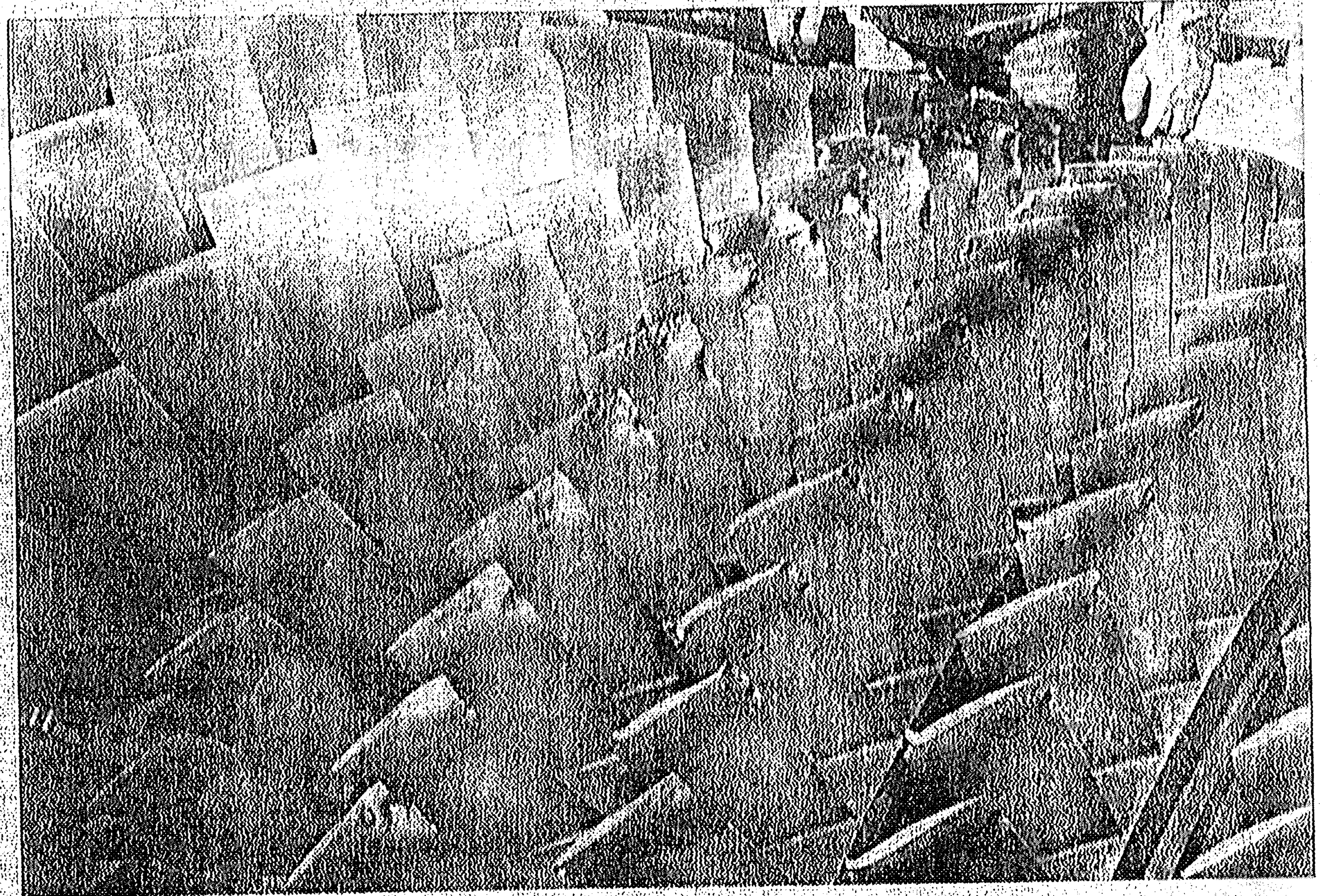
**A.** Well, you've figured out how it works. That's really what it does. It locally linearizes about a point called the most probable point, which is as a mathematical definition, but then it uses linearized perturbations. It uses what's analogous to a steepest decent optimization method to move rapidly to the point of probability at the particular condition you're looking at. So, yes. In fact, there are a couple of time-saving methods. One is a linearized approach and that typically provides about a factor of 1000 reduction in the number of simulations you have to do. Another method is called selective sampling. It uses the most probable point to avoid doing many of the simulations. If the random number generator puts a point inside the circle, you know in advance (your most probable point tells you) the size of that circle. You know in advance that you don't need to bother with that point. So it allows you, by knowledge about the space to make decisions that can greatly save on the number of simulations. So those are a couple of the advanced techniques NESSUS uses. But you're right on, it's a linearized perturbation analysis.

# *Damage Mechanisms Involving Seals & Secondary Flows: The Potential for Beneficial Application of Probabilistic Methods in Design & Decision Making*

- *Some Important Damage Mechanisms Involve Seals or Secondary Flows*
- *Modeling, Measurement, Damage Criteria, Subject to Uncertainty*
- *Probabilistic Methods ⇨ Help Manage Uncertainty:*
  - *New Framework for Engineering Analysis/ Recommendations*
  - *Support and Enhance Economic Design Analysis*
  - *Currently Underutilized*

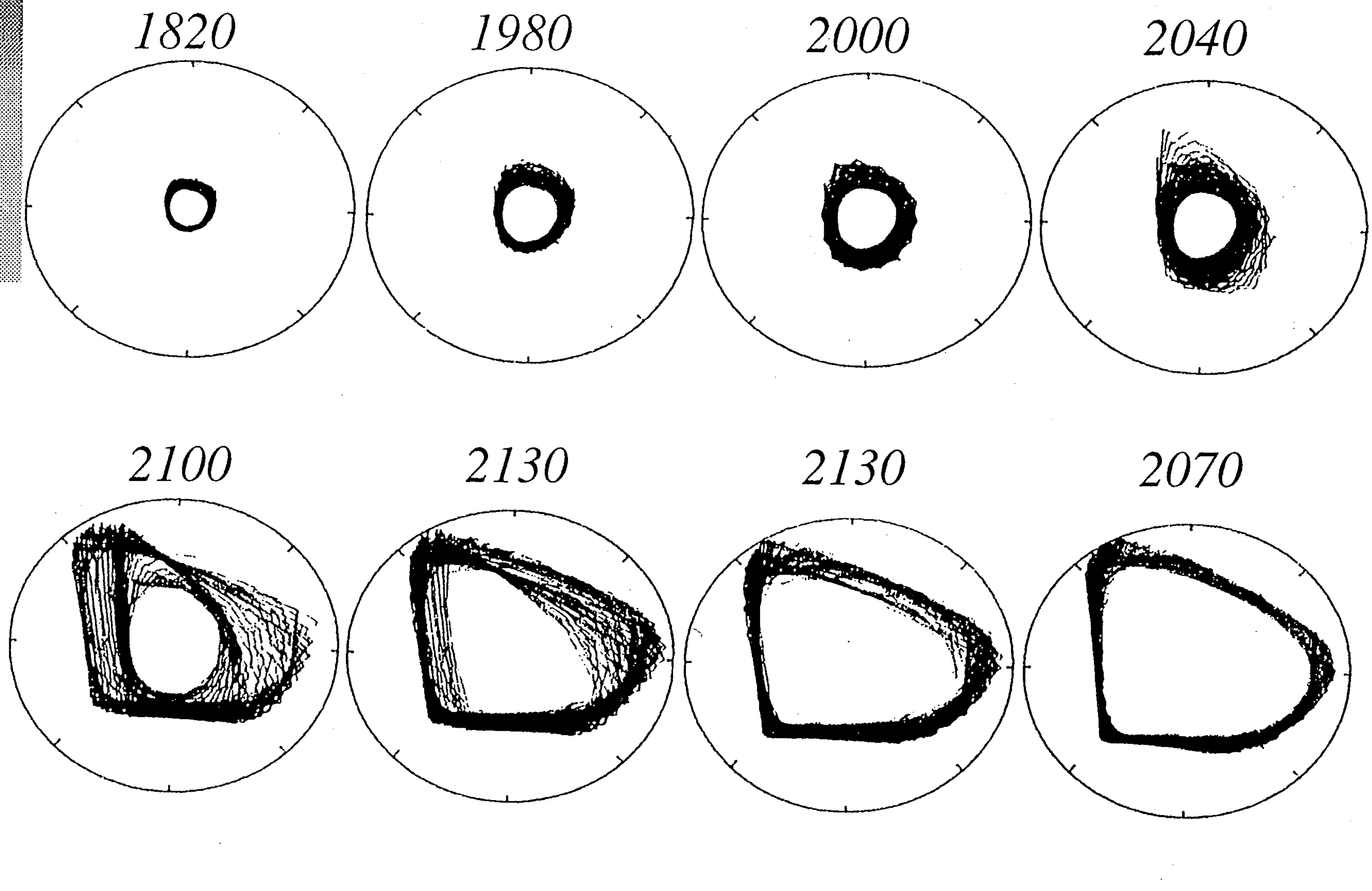
# Examples of Damage Mechanisms

- Seal Rubs Due to High Vibration and Misalignment
- Stall Induced Vibration in Centrifugal Compressors
- Turbine Blade Failure Due to Forced Vibration
- Compressor Blade Failure Due to Material Imperfections
- Consequential Damage from Tip Rubs Due to Casing Distortion

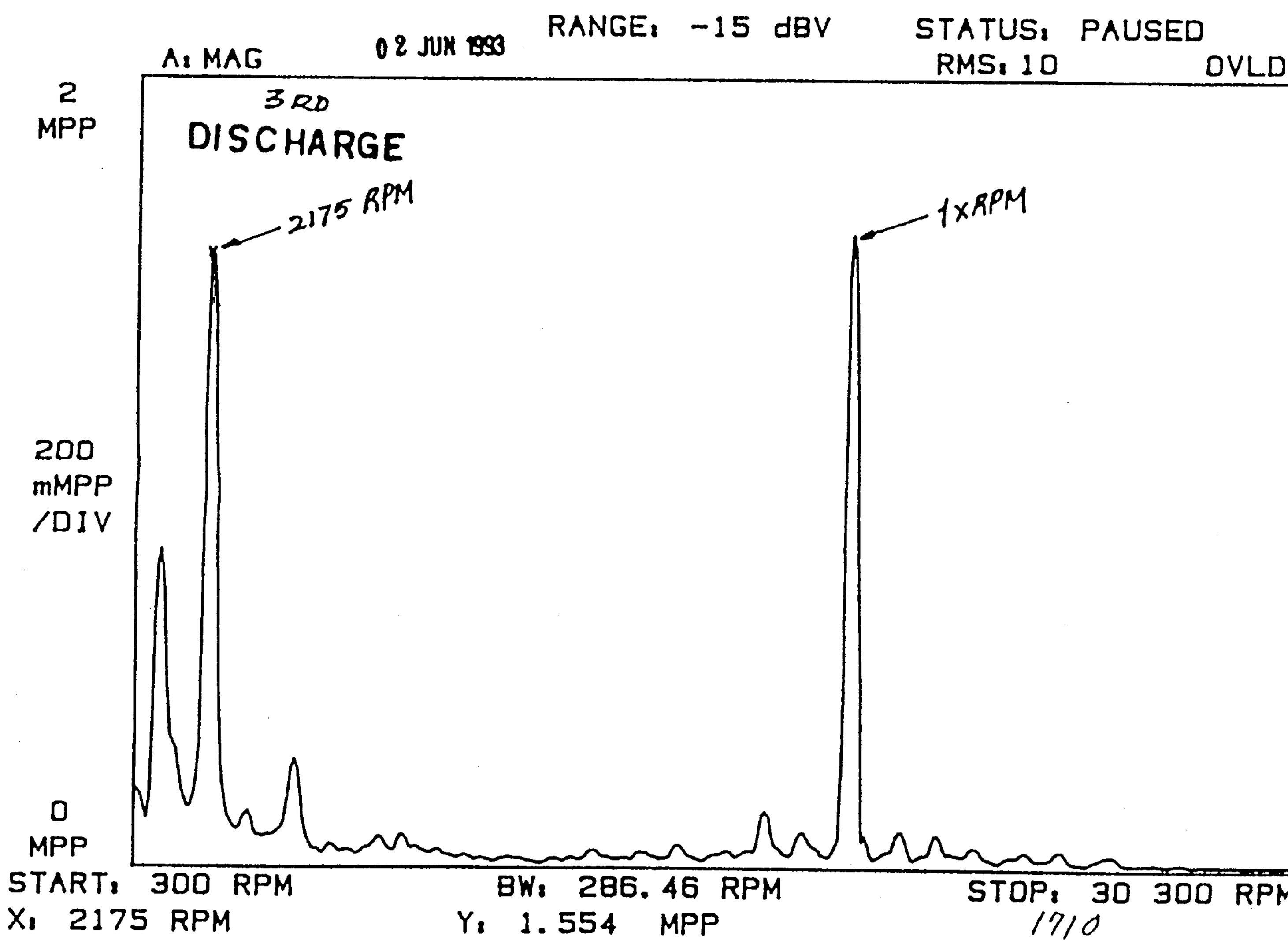


Consequential Damage from Tip Rubs

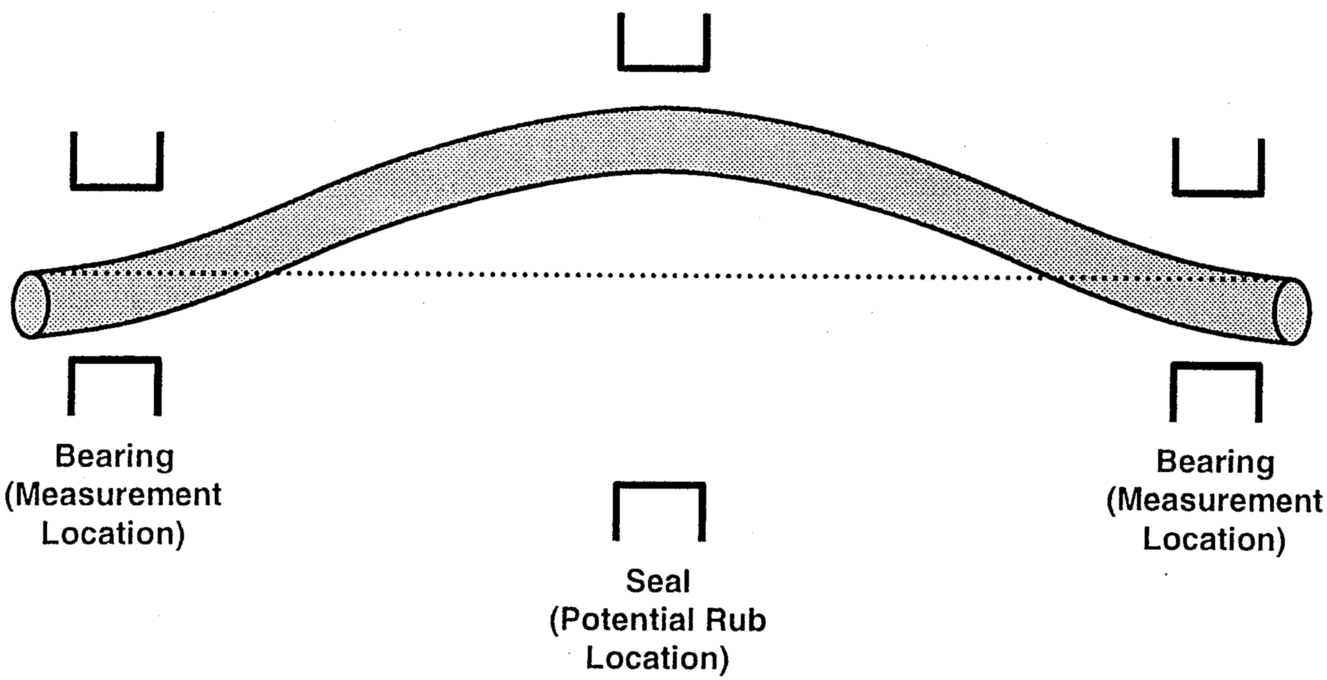
# *Seal Rub Orbits with Changing Speed (RPM) - Circle Diameter = 10 Mils*



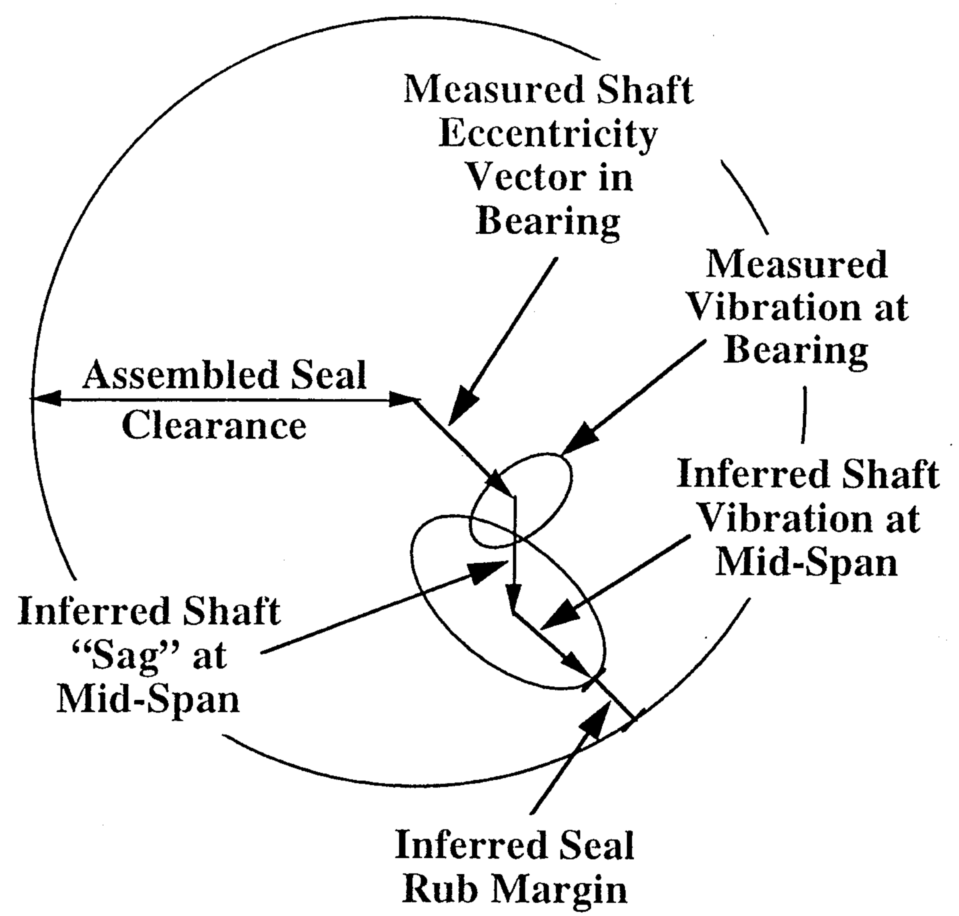
# Example of Vibration Induced by Diffuser Stall in 20,000 RPM Centrifugal Compressor



# *Schematic of Whirling, Eccentric Rotor with Locations of Measurement & Potential Seal Rub*



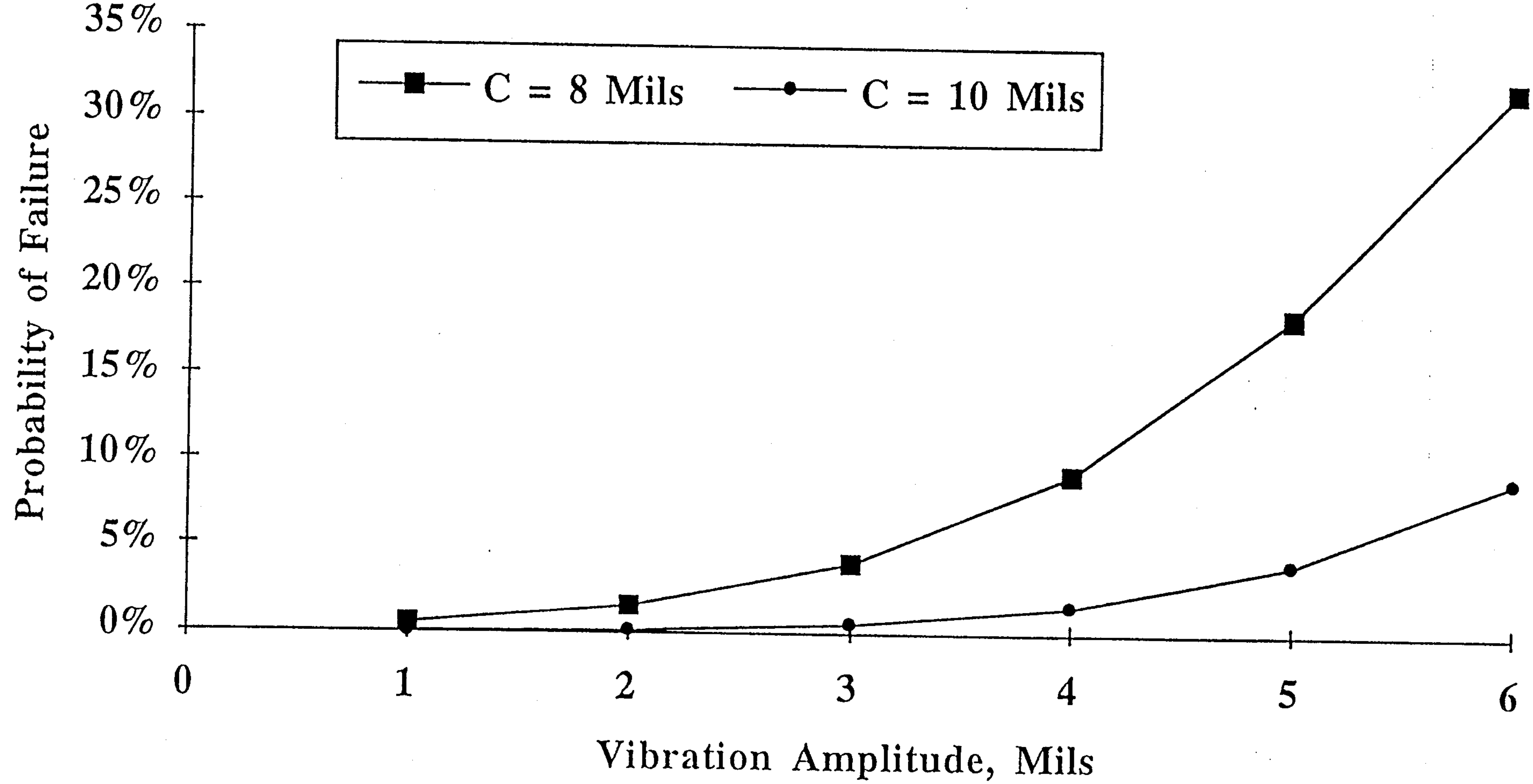
# *Schematic Showing Vector Quantities Measured, Inferred, or Assembled Which Combine to Give Inferred Seal Rub Margin at Mid-Span*



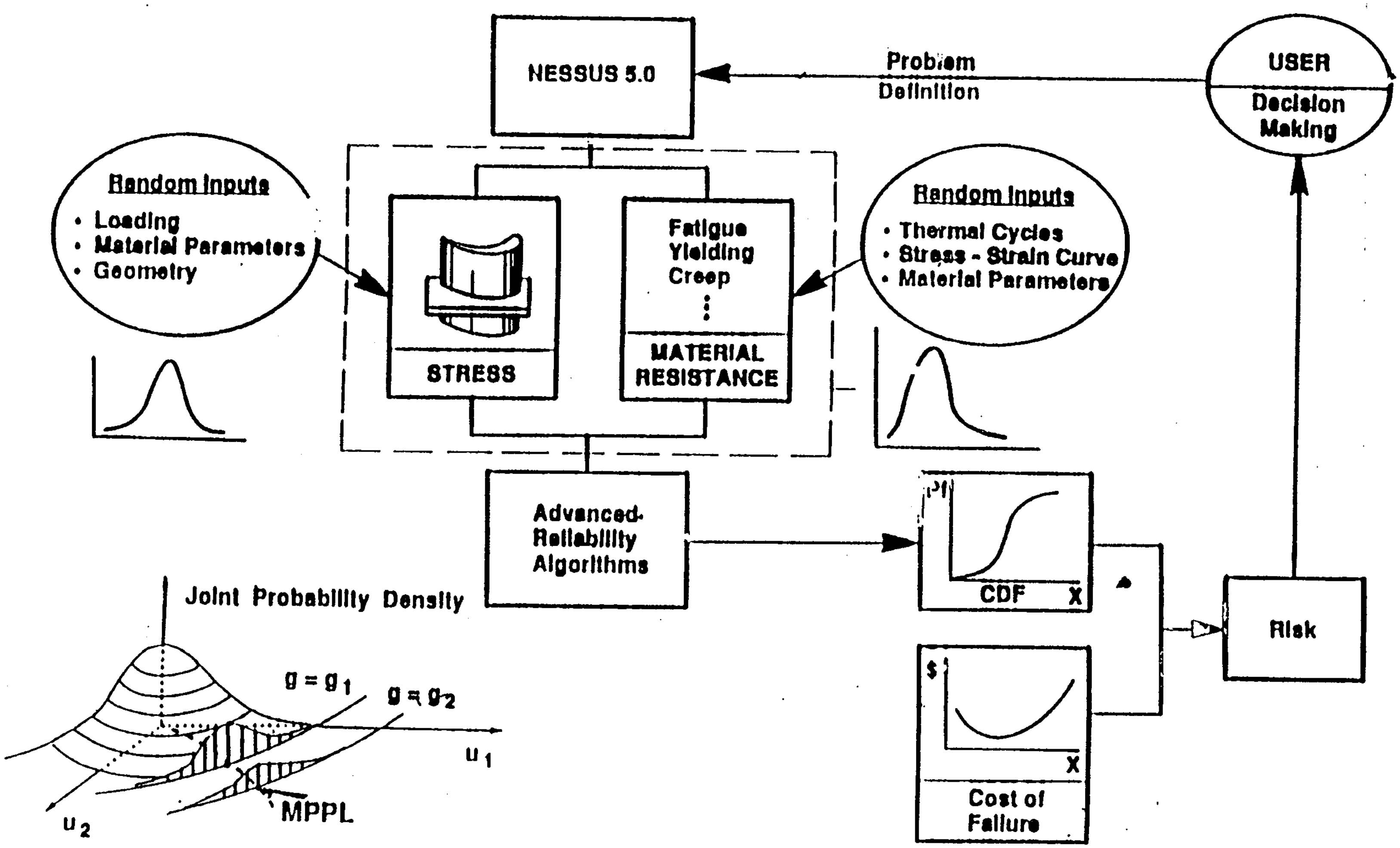
# *Contributing Uncertainties in Seal Rub Assessment*

- *Shaft Mean Position* — *Estimated COV=10%*
- *Measured Vibration* — *Estimated COV=10%*
- *Vibration Multiplier at Seal* — *Estimated COV=20%*
- *Seal Clearance* — *Estimated COV=15%*
- *Rate of Clearance Increase Due to Rub*
- *Risk of Catastrophic Failure from Rub*
- *Dependence of Efficiency Loss on Clearance Increase*

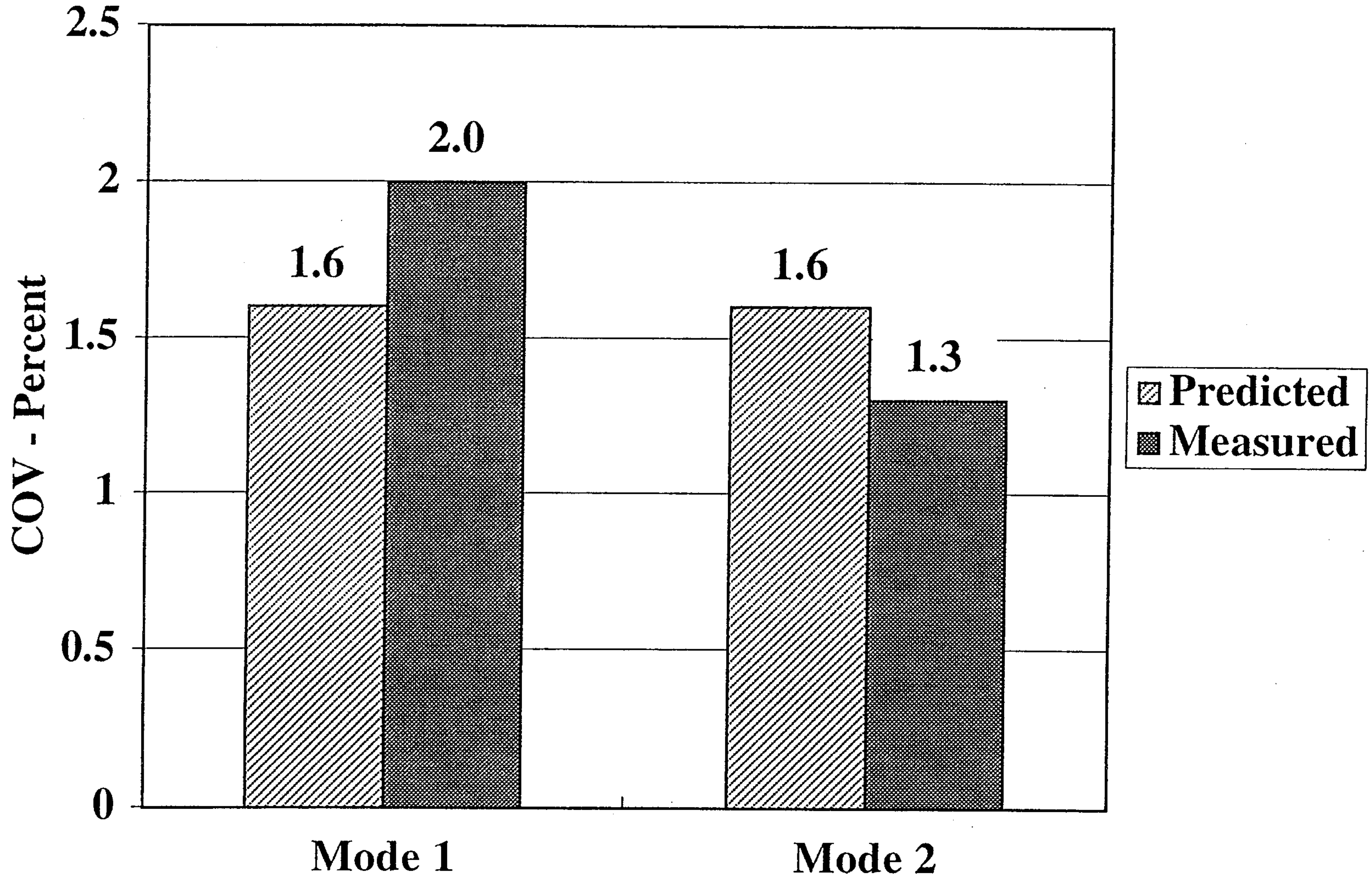
# PROBABILITY OF SEAL RUB AS A FUNCTION OF MEASURED VIBRATION AMPLITUDE AT THE BEARING



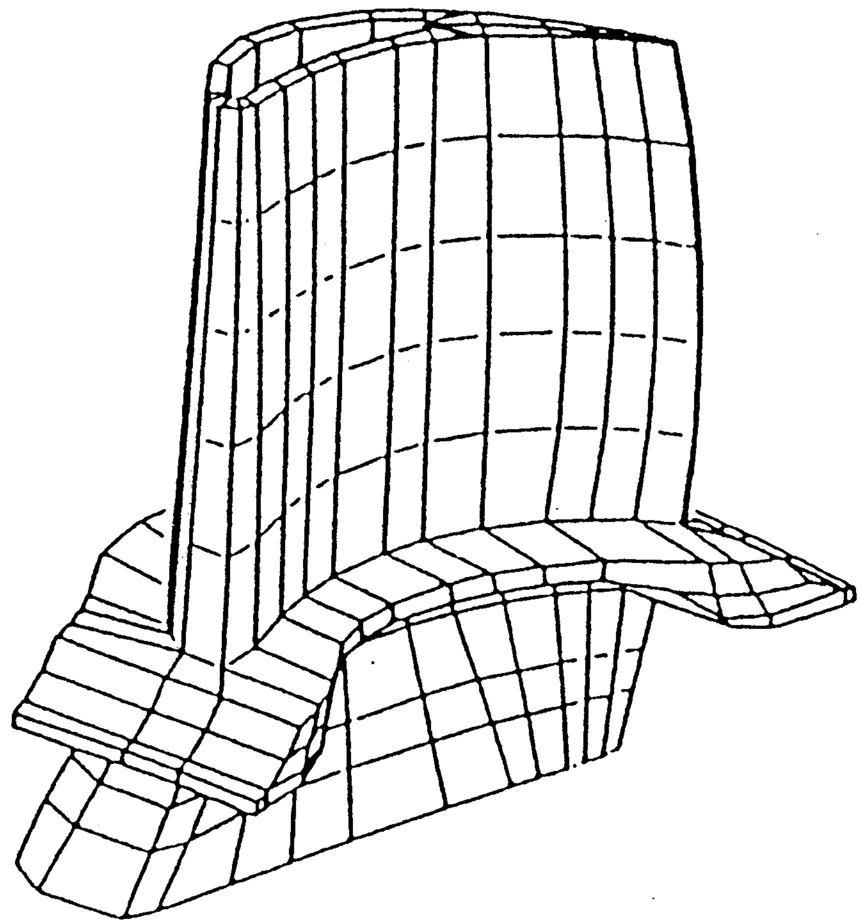
# NESSUS 5.0 - Component Reliability, Resistance, and Risk



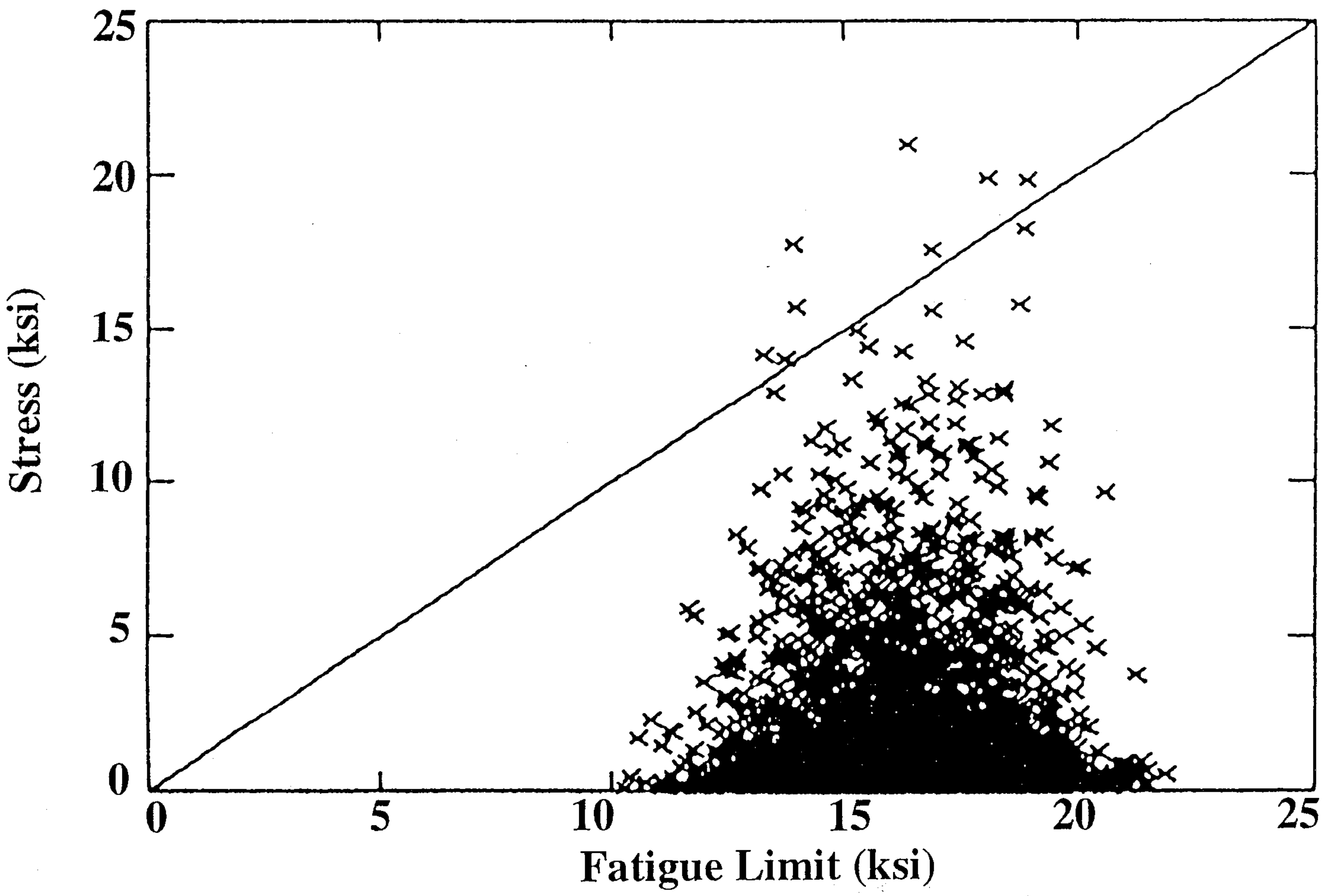
# *Predicted and Measured Coefficient of Variance*



# Probabilistic Natural Frequency Analysis



# *Monte Carlo Simulation L-0 Blade Fatigue Failure**




* Courtesty of Paper No. C500/122/96, "Risk Assessment of Low Pressure Steam Turbine Blades," by T. C. T. Lam and N. F. Rieger, Sixth International IMechE Conference on *Vibrations in Rotating Machinery*, September 1996.

# TURBINE ROTOR MATERIAL DESIGN

Sponsor: Federal Aviation Administration
FAA Technical Monitor: Mr. Bruce Fenton
SwRI Program Manager: Dr. Gerald Leverant

*Program Team:*

AlliedSignal Aerospace
Allison Engine Co.
General Electric Aircraft Engines
Pratt & Whitney Aircraft
Southwest Research Institute

# *Turbine Rotor Material Design*

## ***PROGRAM GOAL***

*To improve the safety of the commercial airliner fleet by developing a generic, probabilistically-based damage tolerance design code to augment the current safe-life approach for design and life management of gas turbine rotors.*

## ***INITIAL PAYOFF***

*For new airliners that join the fleet over the next 20 years, a significant reduction in the 1984-1989 uncontained disk failure event rate due to titanium melt defects ($1.4 \times 10^{-8}$ per engine cycle).*

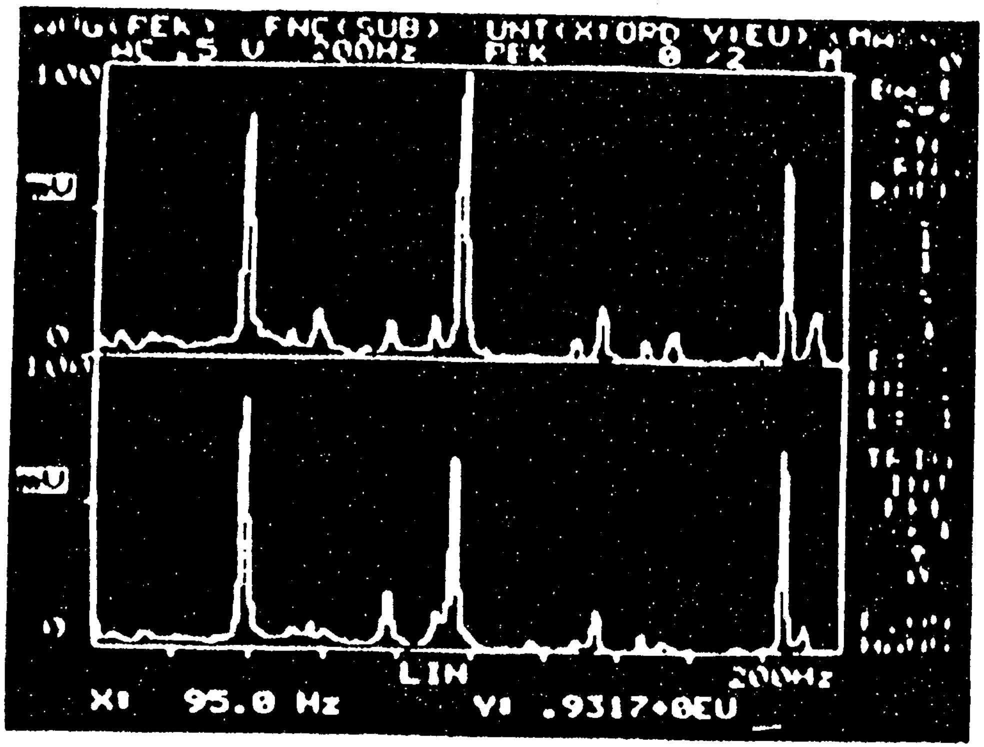
# *Other Decisions Potentially Enhanced by Probabilistic/Economic Analysis*

- *Rotor Bearing Design and Choice of Shaft/Bearing Dimensions, Seal Clearance*
- *Whether to Shut Down a Revenue Generating Machine with High Vibration*
- *Whether to Start a Turbine Based on Slow Roll Runout*
- *Inspection Intervals for NDE*

# *Need for New Approach to Vibration Shutdown*

- *Operators Run Machines to Make Product and Profit*
- *Shut Down to Balance, Align, Diagnose Cuts Revenue*
- *Running with "Excessive" Vibration Risks Damage, or Forced Outage*
- *We Need Economically Meaningful Ways to:*
  - *Measure When we Reach "Excessive" (Sense & Diagnose)*
  - *Quantify $ Risk (Predict)*
  - *Optimize Benefits Vs. Cost (Decide) (Avoided Shutdown Vs. Expected Damage)*

# *Diffuser Stall - Vibration Spectrum for 11,000 RPM Rotor*

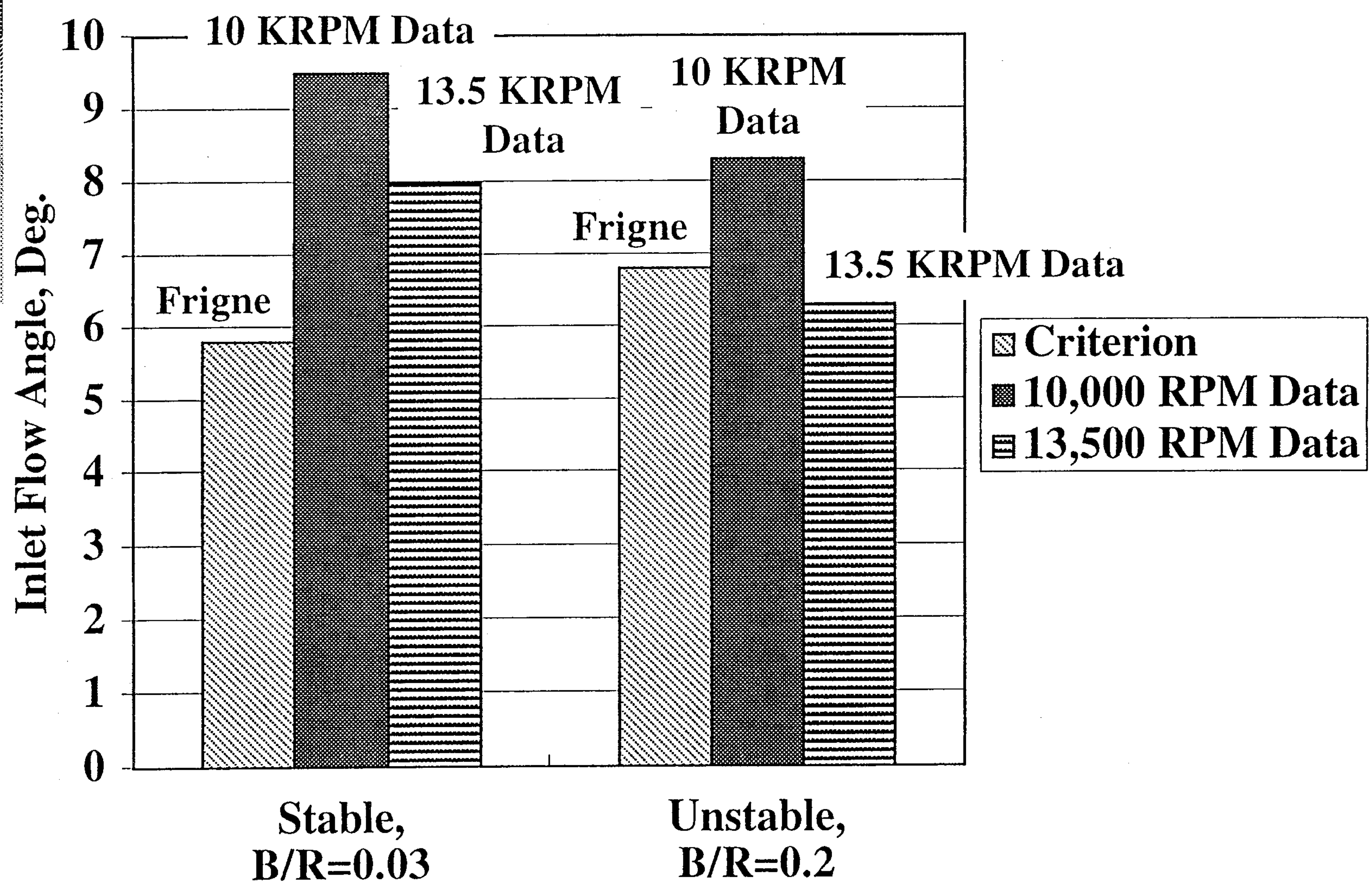



NDEX

AT 1850 PSI; 11,100 RPM

AT 1760 PSI: 11,100 RPM

# *Comparison of Test Data Vs. Diffuser Stall Criterion of Frigne (Von Karman Institute)*



# *Uncertainties in the Engineering of Diffuser Rotating Stall Problems*

- *Operating Envelope of Pressure/Flow Conditions*
- *Local Geometry Tolerances*
- *Gas Properties*
- *Dependence of Diffuser Flow Angle on Geometry, Speed, Gas Flow and Properties*
- *Influence of Seal Shunt on Diffuser Discharge Flow and Flow Angle*
- *Dependence of Maximum Diffuser Width on Diffuser Flow Angle*
- *Magnitude/Frequency/Location of Excitation Should Stall Occur*
- *Sensitivity of Rotor/Bearing Response to Subsynchronous Excitation*

# *Summary*

- ***Probabilistic Methods***
  - *Underutilized*
  - *New Framework for Quantitative Decisions*
  - *Dovetail with Economic Design Analysis*
- ***Promising Fields***
  - *Rotor Dynamic Design*
  - *Vibration Severity - Shutdown Management*
    - *Seal & Tip Rubs*
    - *Bearing Fatigue*
  - *Stall Occurrence and Severity Control*
  - *Robust Design*