AGILIS

Non-Intrusive Stress Measurement Systems

Fundamentals

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Overview

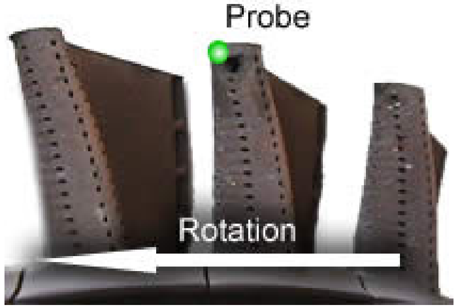
The Non-intrusive Stress Measurement System, or Blade Tip Timing, is a turbo-machinery testing technology that uses static, external sensors to determine vibration induced stresses and frequencies in rotating turbo-hardware.

NSMS externally mounted sensors provide a flexible, cost effective, and reliable alternative to strain gauges. Measurement is non-invasive and comprehensive in its characterization of all blades. The long-lasting, low maintenance nature of NSMS hardware allows for long-term as well as short term stress characterization, and engine health monitoring.

Externally Mounted Sensors

NSMS instrumentation consists of a set of case mounted probes that accurately determine the arrival time of a blade tip at a particular case location. Optical, capacitive and eddy current probes can be used for the arrival time measurement.

The example blade (fig.1) demonstrates how case mounted probes (red) placed at unequal distances record an arriving blade tip (green). Probes are placed at pre-determined locations around the case. These locations are calculated by AMS software to optimize observation of specific engine orders.



Minimal effect on blade vibratory characteristics

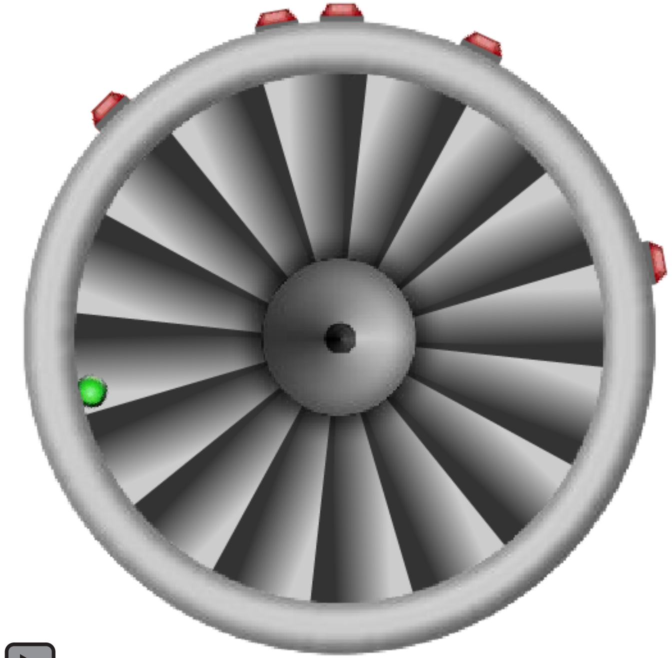


Fig. 1: Front View

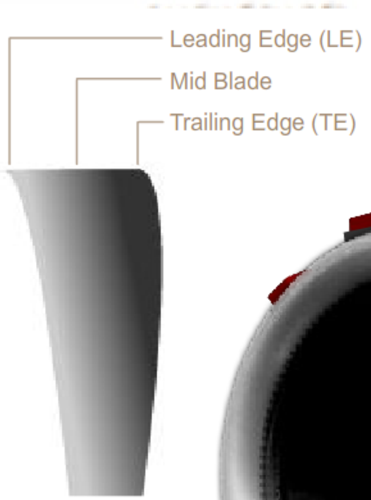
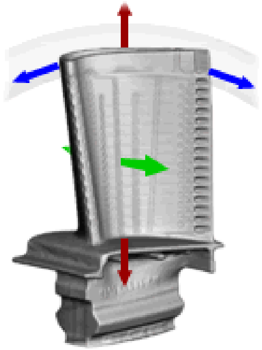


Fig. 2: Blade

Fig. 3: Side View

Various Measurement Capabilities

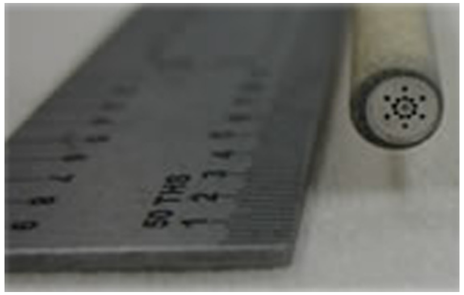
NSMS probes can be configured to measure any component of the dynamic deflection such as axial, tangential, radial.



The example shows the directions of axial (green), tangential (blue), and radial (red) deflections on a blade.

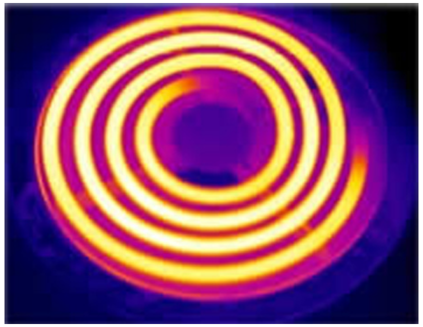
High Temperature Capabilities

Another AMS advantage is our high temperature capability. Agilis Measusrement Systems can test in high resolution using optical probes in environments exceeding 1800 degrees Fahrenheit. Superior materials selection and design make testing on rocket pumps and high pressure turbines possible.



High Temperature Probe

Other problems commonly associated with higher temperatures (such as black body radiation) are negated by utilizing laser line (infrared) filters.



Blackbody radiation coming off a stove top

Dirty Gas Path

Purge air forced through the probe bodies and out of the heads keeps the optical heads clean while regulating probe temperature. In the dirtiest environments, high quality Eddy Current probes record blade passings with crystal clear accuracy.

Event Time Determination

When has the blade arrived?

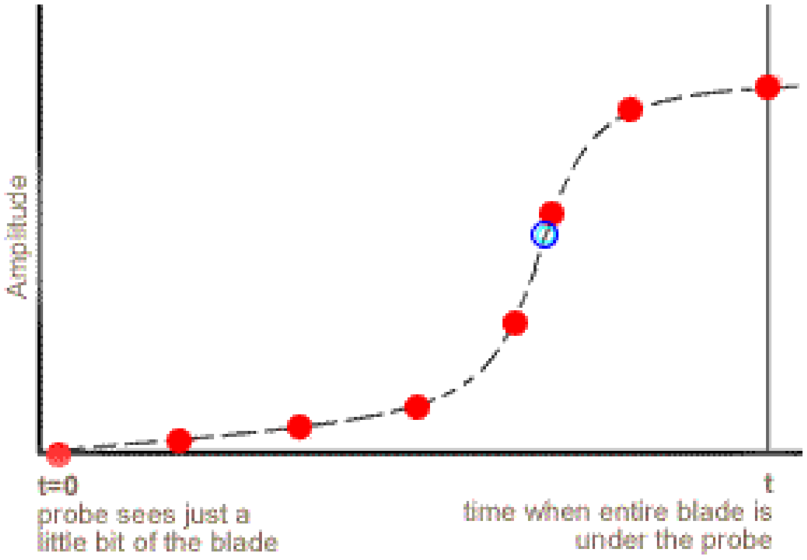
The arrival time of the blade is an important question. Imagine you are in very slow motion, slow enough that you are able to take a picture every 2 nanoseconds (that’s 0.000000002 seconds). You are taking a picture that is a certain size (this is called your spot). As the blade approaches, a part of the blade edge catches the edge of the picture “frame”; this is recorded. Also, the strength of the returning signal allows you to know how much of the blade is being seen. Imagine you have 8 pictures from the time the blade tip first enters in to the viewing frame of the spot until the entire blade is under the spot. The blade arrives halfway between when the probe first senses the blade beginning to pass and when the entire blade is over the blade.

What defines this discrete event?

From the amplitudes and times of the 8 pictures taken over the course of a blade encounter, a curve or line is fitted to these points; then an “event” can be defined as the point of max amplitude change, and the corresponding time along with it. This method provides highly accurate event descriptions and allows AMS the ability to see responses on the sub-1 mil scale.

On the graph, the red dots represent the pictures taken; each dot has an amplitude and a time. Our system takes these points and fits a curve (dashed line) to these points. This allows us to take the best possible time at our “event”, shown in blue.

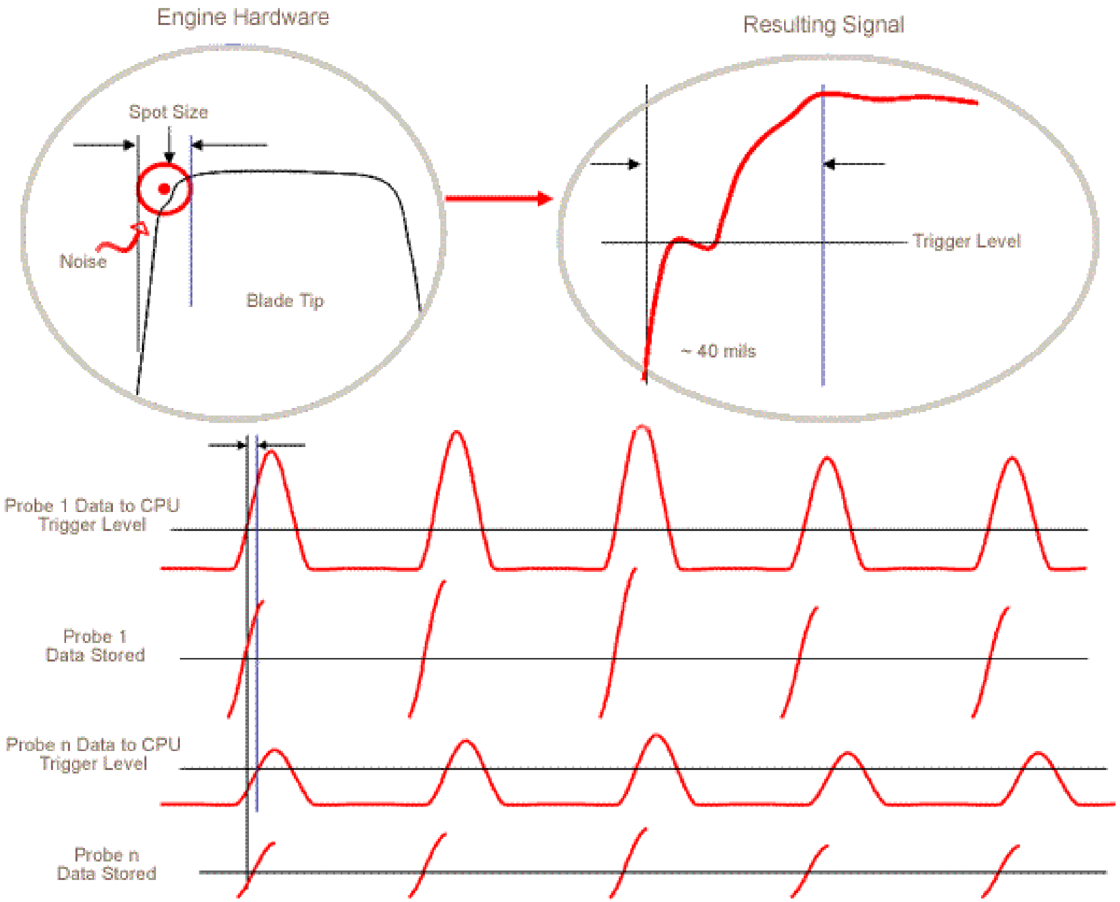
Event Definition



Event Time Determination

What is the measurement resolution?

Trying to define our resolution is a complex task. In terms of accuracy, our digitzer cards are on the order of .000000002 seconds. Resolution, however, is theoretically much higher because the event times we are recording come from a curve fit interpolation, and not any specific data point. An important factor is the spot size. AMS optimizes the spot on the blade tip to be small compared to the blade size but large when compared to the surface texture.



The AMS realtime system records all 8 points during acquisition. This allows the user to adjust even time triggers during post-processing.

Arrival Times to Deflection Conversion

The arrival times of each blade are converted to blade positions relative to Once Per Revolution (OPR), or "center time" by using the rotational velocity and the radius of the measurements. In the analysis portion, there blade positions are then compared to a precisely calculated "undeflected blade position", to yield a deflection value for each blade.

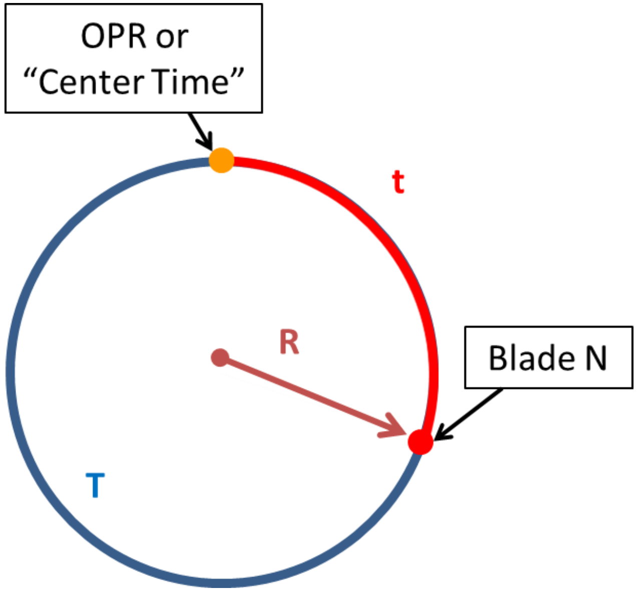
$$X = Vt=2*pi*R(t/T)$$

Rotational Velocity (V) = revolutions / minute

Radius to blade tip (r) = inches

t = time from measured blade event to measured blade event

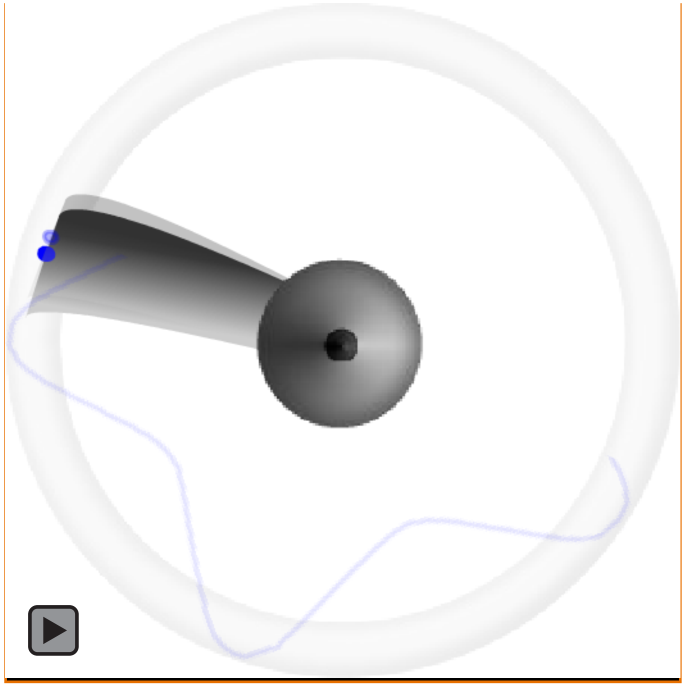
T = time for one revolution of all the blades



Arrival Times to Deflection Conversion

Blade Tip Timing

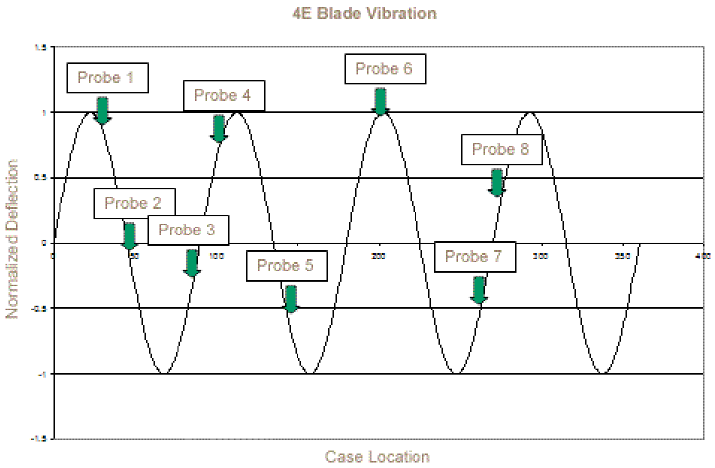
In the blade tip timing example, the green line is the actual arrival time for mid-blade edge (blue dot) of a particular blade as measured by an AMS probe. The red dashed line is the center-time for a blade passing. The center time is calculated using the arrival times of all the blades and averaging them over 3 revolutions. The time difference (black arrow) represents the difference between when the blade should pass and when it actually does. Following the blade is a 5E (five vibration/one rotation) Sine wave. The difference value is converted into blade deflections and used in the overall blade analysis.



Arrival Times to Deflection Conversion

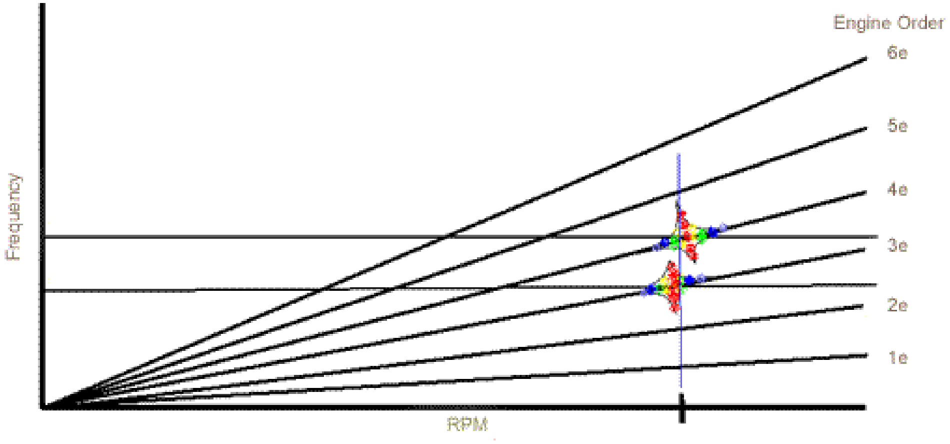
Blade Vibrations

Data from multiple probes at a common axial location are used to determine the mode frequency of a vibration. Once fit, amplitude and phase data can be calculated along with engine order, peak response rpm, data fit, absolute phase, damping, and other vibratory characteristics.



Probes are placed in specific locations around the case of the given application to optimize on certain (pre-specified) engine orders.

This means that the locations of the probes allows for more accurate data around the regions where resonances are bound to occur.

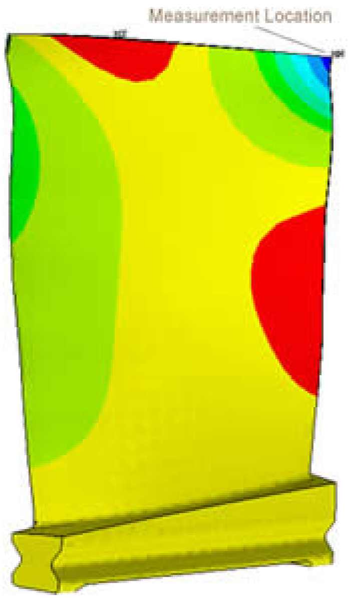


When solving for a resonant frequency as mapped as a sinusoidal oscillator, it is necessary to view the response at three points along the phase of the vibration; therefore, 2N + 2 probes are required to analyze N simultaneously occurring blade vibrations.

Deflection to Stress Conversion

The deflection measurement is a peak-to-peak measurement derived from the axial and tangential deflections of the rotor blade. The shape of the modes in interest, as well as the probe's axial position on the blade (leading edge, mid blade, trailing edge), determine the sensitivity the NSMS system will have to a particular mode.

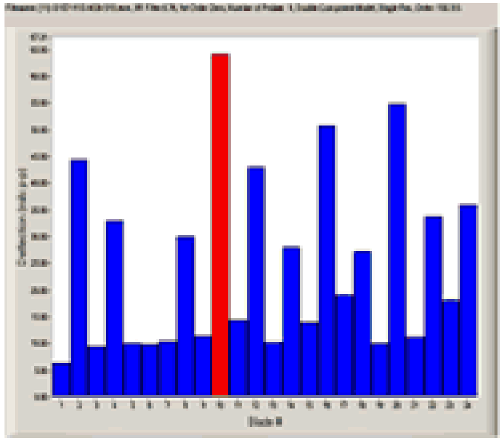
If sensitivity to many modes, or complex modes, is desired, multiple groups of probes placed at different axial locations are utilized. This allows not only for greater mode sensitivity, but will confirm the validity of actual mode shape models. Once all necessary deflections are measured, Stress/Deflection ratios From FE models can be input to calculate corrosponding stress levels.



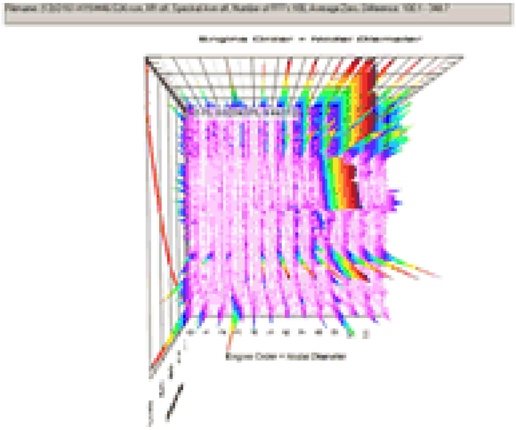
Example Finite Element Model

Complete System Characterization

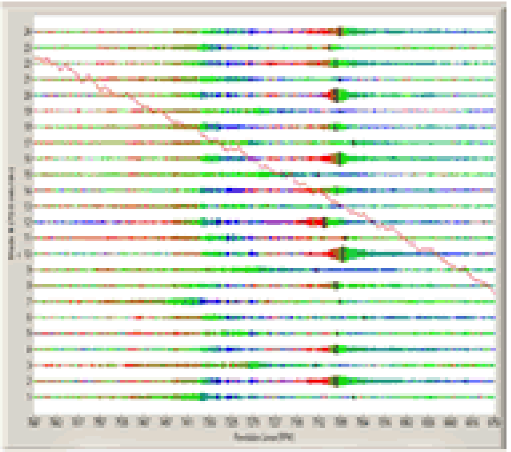
The ability of NSMS to "see" every blade provides valuable data on the system behavior of a response. The software system can be categorized into 3 main components. The first component includes all software which is used during test setup; including simulating expected responses, optimizing probe locations, and building Campbell diagrams. The second component is our Real Time analysis, which has the capability of analyzing both non-synchronous (buffet, flutter, stall/surge) and synchronous (single and multiple resonant responses with full amplitude, phase, frequency, and damping calculations) responses as they occur on a test. The final component is the Offline Analysis, which includes all post processing. In addition to including the same synchronous and non-synchronous data analysis, Offline provides data conditioning, batch analysis, presentation generators, and an abundance of data reduction calculations meant to give the user a maximum description of a blade or blade system's dynamic characteristics.



High Responding Blade



Nodal Diameter Content



Frequency mistuning and blade interactions.

Engine Health Monitoring

The robust case mounted characteristics of the NSMS probes also allow for use as an engine health monitoring sensor.

- FOD detection
- Blade crack detection through changes in the HCF behavior
- Erosion monitoring
- Flutter detection
- Rotor rotational changes from bearing degradation

Field Investigations

NSMS probes can be developed for standard engine borescope ports. This allows for rapid field investigations, significantly reducing the pre-test timetable.

Flexible Test Scheduling

Because the NSMS system uses robust case mounted sensors, the system can be maintained throughout an extended test period.

Instrumentation mortality which is common with conventional strain gages does not dictate the order of the test schedule.

As well as being more reliable; AMS probes are reusable, affordable, and above all, accurate.

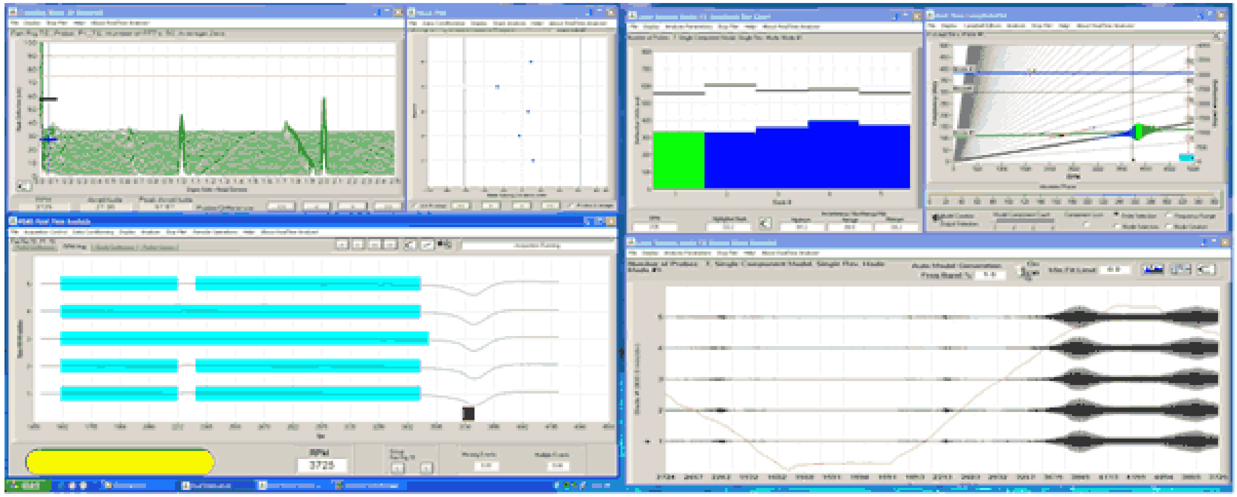
Ease in setup allows AMS systems to cover short term multi-application (same probes used on multiple housings) tests while Satellite communication and remote system monitoring capability allows tests to be conducted for extended periods of time.

The Testing Schedule is driven solely by the customer.

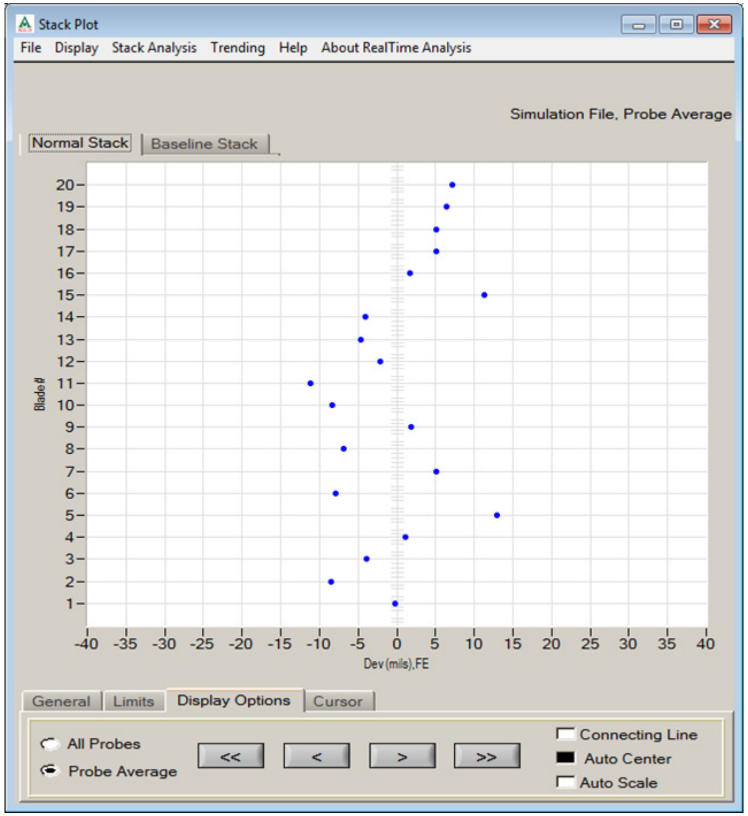
Synchronous Realtime Analysis

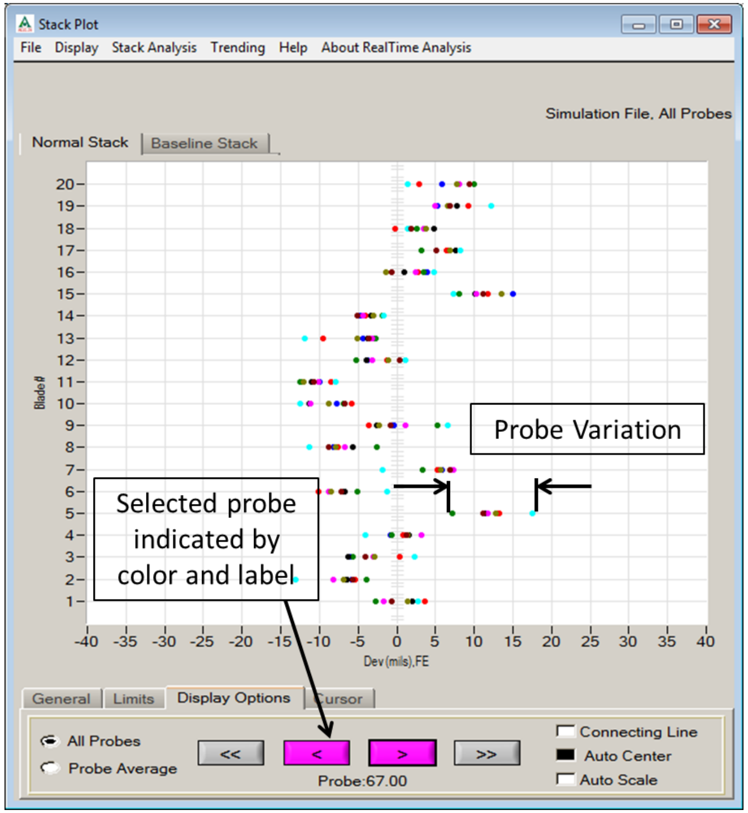
Realtime Synchronous analysis is performed using LSMF (Least Squares Model Fitting) analysis. This analysis package performs a least squares fitting of multiple, pre-selected, sine wave models. The frequency or order of the sine waves is determined from the selected model components on the Campbell diagrams. The fitted amplitudes and phase values are then displayed in various manners such as bar charts and blade waterfall plots. The bar chart shows the individual blade amplitudes for the selected model component; it displays the maximum, minimum and average statistical values.

The blade waterfall plots display all blades' amplitudes against time traces, rotor speed, or linear revolutions. These plots are useful for understanding blade-to-blade coupling and for monitoring relationships between rpm and resonant responses. As in the above example, Traveling Wave analysis can also be run concurrently. This is useful for non-synchronous response analysis, but also shows any non-stationary synchronous vibrations such as mistuning effects or hardware transmission. A "near-realtime" LSMF analysis is also available; this operates from the data stored in the RPM Map. It is useful for determining resonant rpm values and damping coefficients during engine testing.



Synchronous Realtime Analysis





Probe Variation

Selected probe indicated by color and label

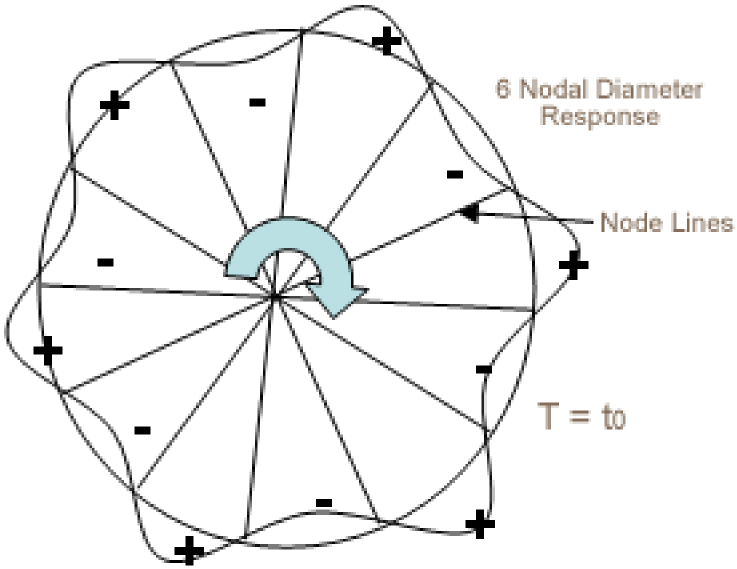
Stack Plot

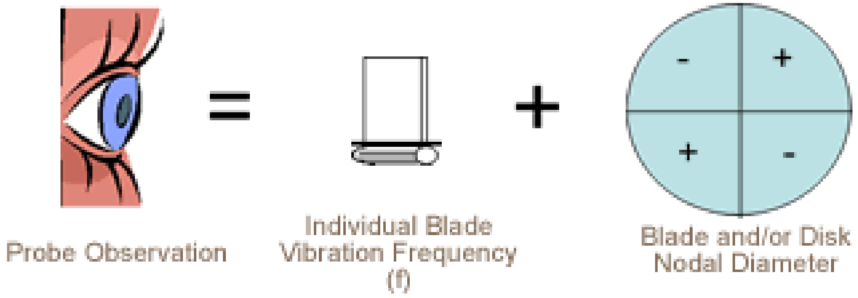
A stack plot, such as the one above, displays the variation in the inter-blade-spacing from an ideal, equally spaced, blade arrangement. This is useful for monitoring the health of a stage. Consistent deviation from the undeflected or "baseline" stack pattern could indicate the propagation of a crack or some other mechanical misalignment. Foreign object damage (FOD) can also be observed if the damage causes static deflection changes at the probe measurement location.

Non-Synchronous Realtime Analysis (Traveling Wave Analysis)

Observed Engine Order

- Engine Order is the vibration frequency of individual blades
- Nodal Diameter is the relative phase from one blade to the next, it is always an integer, from 0 to ½ the number of blades
- Observed Engine Order = Engine Order + Nodal Diameter
- Observed Engine Order is what a probe (or probe difference) observes from a fixed location on the case when looking at all blades.
- Since we are sampling all blades as a system or single entity the engine order and nodal diameter are observed as one or a summation. Until one of the two is known, the other cannot be uniquely defined





Converting Frequency to Engine Order

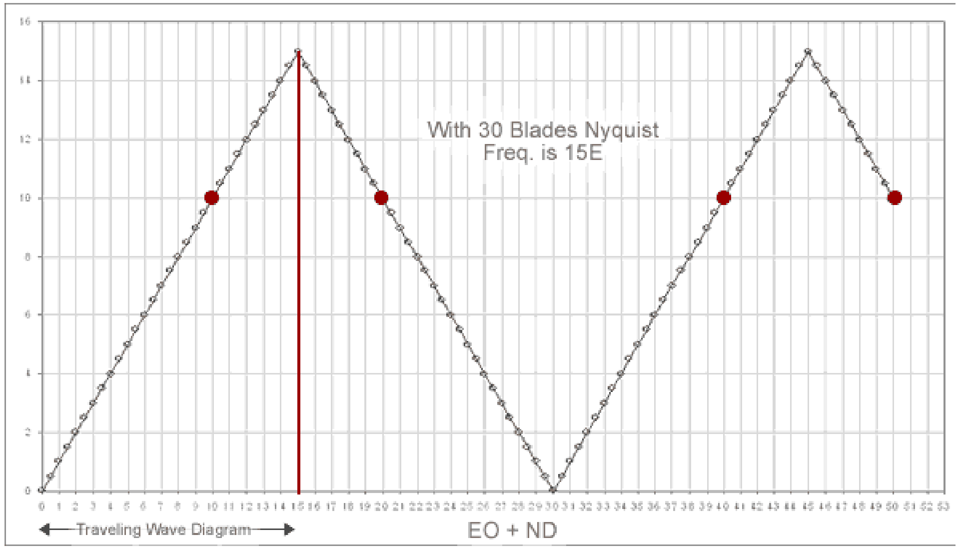
Vibrations are described in their field of study by their engine order.

$$EO = \frac{f \times 60}{RPM}$$

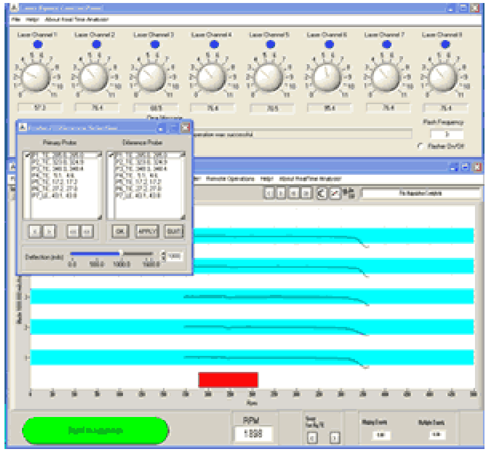
Non-Synchronous Realtime Analysis (Traveling Wave Analysis)

Aliasing

Aliasing is a type of distortion that occurs when digitally recording high frequencies with a low sample rate. A periodic motion (vibration) must be sampled at a frequency of at least 2*fN (Nyquist Frequency) to positively identify the signal, unaliased. If the signal is not sampled at this rate, aliasing occurs, and the vibration can appear to be at a much lower/ higher frequency. NSMS is able to accurately analyze this aliased data by employing multiple probes, and by taking data over multiple revolutions and at varying speeds.



Each probe records only one blade passing time for each blade for each revolution. Most of the observed signal is therefore aliased. Understanding how aliasing effects data is critical when designing analysis tools.



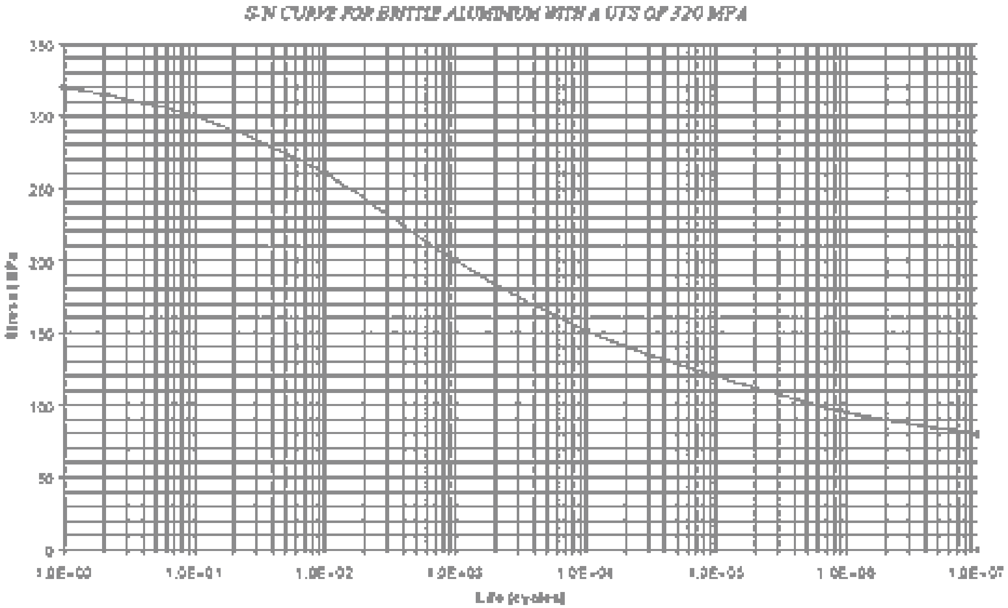
The AMS Non-Synchronous Realtime analysis allows the user to view both individual blades and the entire system in 3 dimensional FFT plots. These functions allow the user to track Mode buffet responses, monitor for crack detection and flutter, and confirm resonant responses, all in real time. The graphical displays and functions are similar to that found in the Offline software.

High Cycle Fatigue

In the pursuit of reducing/eliminating high-cycle fatigue failures in turbine engines, many design and manufacturing paths have been explored. From studying and understanding crack propagation and materials properties to designing blade aerodynamics uniquely suited to an application, a huge amount of time and effort has been spent to eliminate HCF-related failures from the turbine industry.

Vital to understanding and reducing cyclic stresses in a product is an accurate and complete analysis of the vibratory characteristics of the system. Agilis Measurement Systems specializes in monitoring blade vibrations to the extremes of accuracy.

Using NSMS hardware of the highest quality and software unparalleled in the industry, AMS is committed to helping our customers reduce, monitor, and ultimately eliminate High cycle fatigue stresses induced by synchronous and non-synchronous excitations in all turbine applications.



This graph represents a HCF curve for Aluminum up to 1e7 cycles.