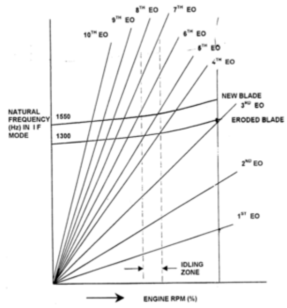

Campbell diagram- Courtesy of Researchgate

Steam Turbines- Part IV- Goodman and Campbell diagrams

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Turbine blades are subjected to many types of forces. These forces can be steady state, such as centrifugal forces, weight and steam strike force, or they can be transient such as forces due to excitation of blades/rotor rotating near critical speed or steam strike force when there is disruption in supply flow. These forces will induce stress and vibration. These vibrations, if neglected during the design of blades, can cause major failure during operation. To analysis these forces and vibrations two curves or diagrams are used namely: Goodman Diagram, Campbell diagram.

Goodman-Soderberg Diagram

Goodman diagram is used to analysis the static and fatigue stresses. In the Goodman diagram the horizontal axis is ultimate strength of the material while the vertical axis is endurance limit; both shall have same dimensions such as kPA or PSI. If the ultimate stress of the material on the horizontal axis connects to endurance limit on vertical axis by a straight line, this line is called failure line. This line is drawn using factor of safety of 1.00. This line means if the stress level falls below this line, the stress analysis as a safe stress. If stress passes this line the material MAY fail. The reason that may is used shown in figure 1. The actual material failure line showed by dashed patterned line. The actual line is found by experiment. So if the stress is above the failure line and below actual line, the material will not fail. However, it is not safe to use the actual line. Factor of safeties can be applied, discussed in the next chapter.

Some companies such as Dresser-Rand (now part of SIEMENS) use Yield strength instead of ultimate strength. In this case the diagram is called Soderberg diagram. Soderberg diagram due to its definition based on Yield strength instead of ultimate strength is more conservative than Goodman diagram.

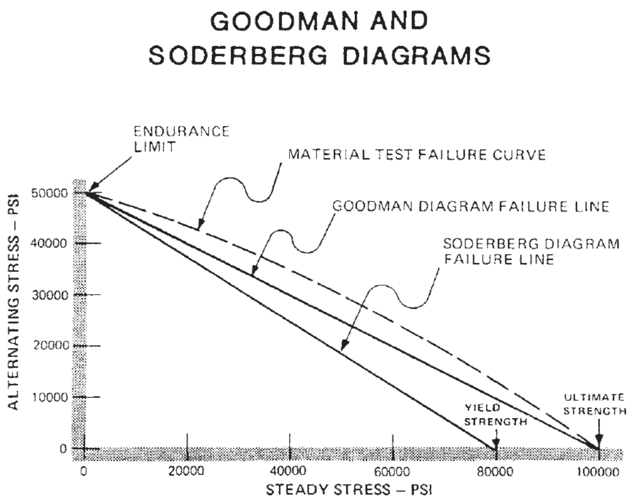


Figure 11.1 Goodman and Soderberg diagrams. *(Dresser-Rand Company, Wellsville, N.Y.)*

> Figure 1- Example of Goodman and Soderberg diagrams

Usage of Goodman-Soderberg Diagram

As mentioned in pervious chapter one has to compare the stress of blade with Goodman-Soderberg diagram in order to find if the blade design are sufficient. So the first step is to calculate the stress on the blades. Stresses are divided into two sections:

1. Steady state stress: this tension stress is due to centrifugal forces acts on blades and bending due to acting force of steam stream on blades. Steady state stress is easier to calculate than alternating stresses.

2. Alternating stress: Please note that this stress is not transient, since transient process is a process that will start and end for example forces that are produces during the acceleration. However, alternating stress can act constantly as long as turbine operates. These forces can be cause due to disturbance in steam flow. Alternating stress is harder to calculate. To calculate alternating stress, experiments and statistics come into account. A formula for calculation this stress is as follow: (stress concentration factor) × (magnification factor) × (steady steam bending stress). In this formula stress concentration factor depends on location. Magnification factor is defined by experimental curves, depends on blade frequency and exciting forces magnitudes.

Factor of safety

Factor of safety is defined since the manufacturing process cannot be perfect. Machine works always contain defects, material casting will not always be homogenous, calculating alternating forces are 100% accurate and so many other factors. The factor of safety is introduced to cover these points.

Stresses acting on blade are now clear. The factor of safety can be defined based on following formula:

$$\frac{1}{\mathrm{FS}} = \frac{\mathrm{steady}}{\mathrm{YP}} + \frac{\mathrm{vibratory}}{\mathrm{EL}}$$

> Figure 2- Factor of safety formula

The factor of safety is defined when plotting steady stress in horizontal axis and alternating or vibratory stresses in vertical axis, as showed in the figure 2.

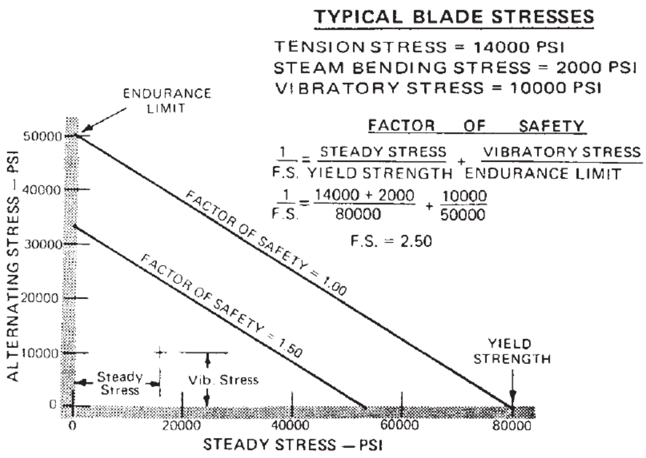


Figure 11.2 Calculating a factor of safety using the Soderberg diagram. *(Dresser-Rand Company, Wellsville, N.Y.)*

> Figure 3- Factor of safety diagram

In reality higher factor of safety means more conservative design. Conservative designs costs more and it is not economical to use conservative design. Selecting sufficient factor of safety is a key factor that separates an experienced manufacturer from inexperience manufacturer. Factor of safety around 1.50 is an acceptable value, but this figure can vary based on manufacturers' experiences.

Campbell diagram

Interference or Campbell diagram is used to analysis vibratory stress level at different stages of turbine operations. Considering major failures caused by vibratory stresses, purchasers usually ask for this document. In our experience, we always ask for this document.

Campbell diagram has turbine speed in RPM plotted on X axis against frequency, in cycle per second or Hz, on Y axis. A typical Campbell diagram is shown in figure 4. When Blade frequency is equal to exciting frequency, or collides, resonance will happens. Blade (Natural) frequency is function of its mass and stiffness. As learnt during dynamics course, each piece of equipment has different natural frequency, each with its own "shape". The following figure shows the natural frequency with the resonance modes.

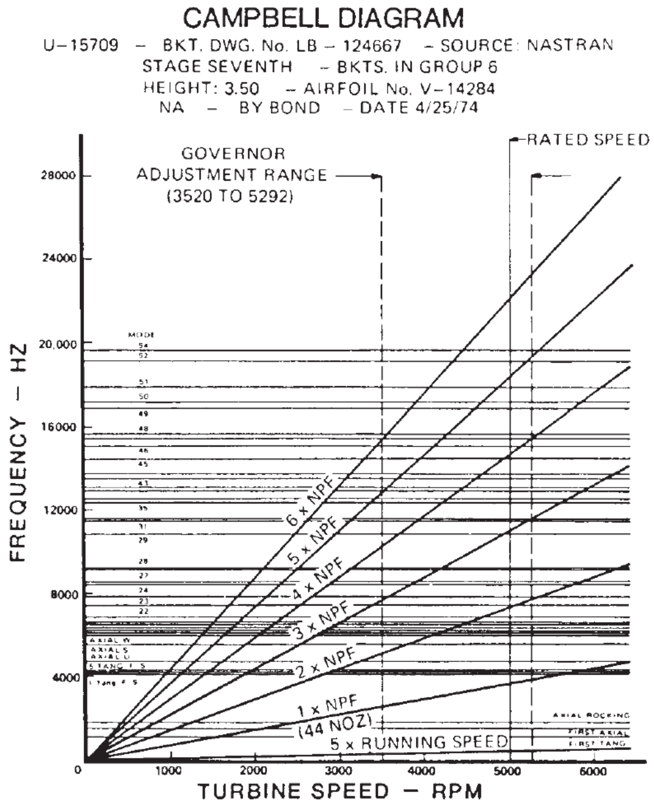


Figure 11.3 Campbell, or interference diagram. *(Dresser-Rand Company, Wellsville, N.Y.)*

> Figure 4- Sample Campbell diagram, NPF= Nozzle Passing Frequency

Figures 5 and figure 6 show different resonance responses for a specific blade. The frequency swept from 300 Hz to 10000 Hz.

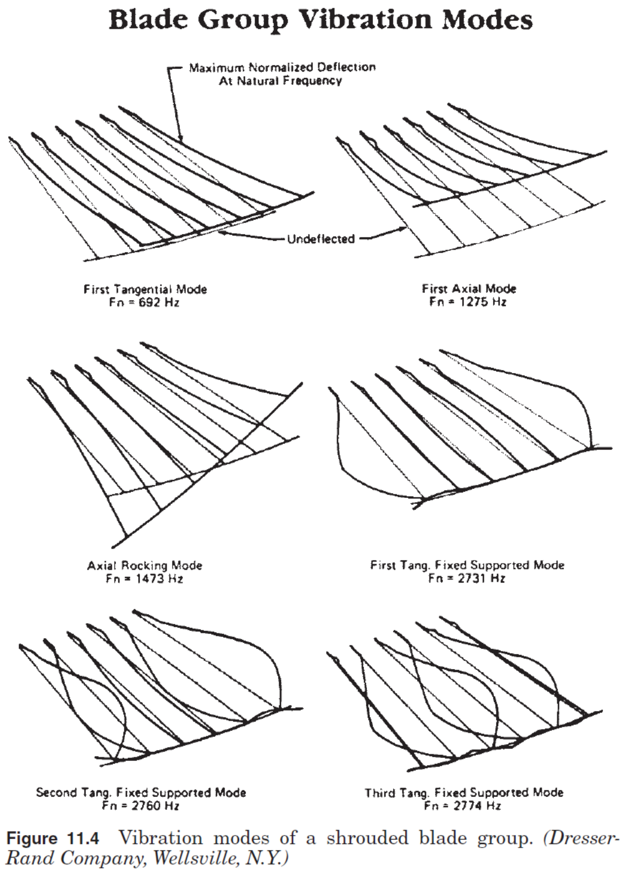


Figure 5- Different excitation modes

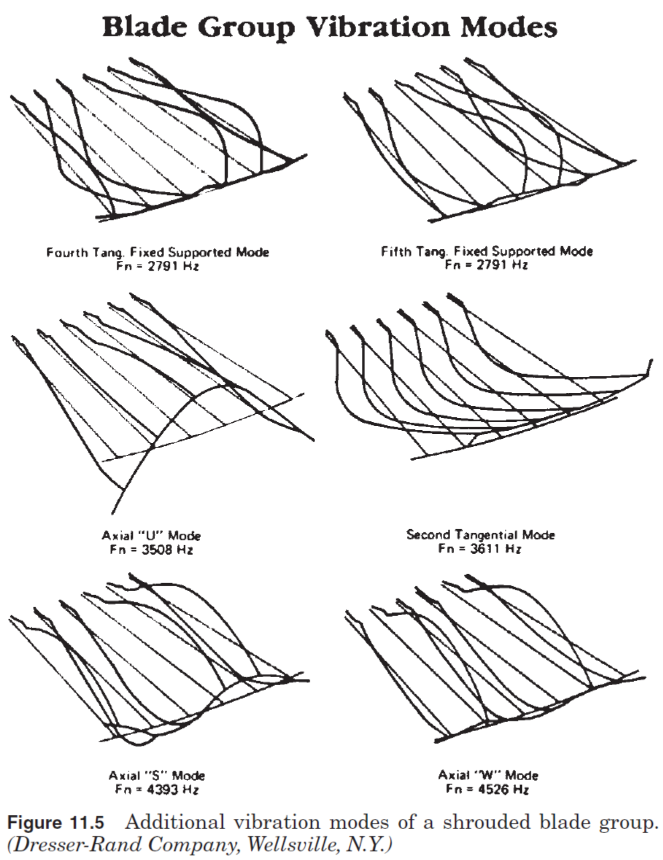


Figure 6- Different excitation modes- Cont.

Campbell diagram interpretation.

Before jumping to Campbell diagram interpretation, a term shall be defined:

Engine Order Line or EO line: Engine order is a periodic force. The frequency of harmonics of turbines defined with following formula:

$$f_i = \frac{n * \Omega}{60}$$

> Figure 7- Frequency of harmonics- Courtesy of **KTH**

In which Omega is rotation speed in RPM and n is engine order. By variation of rotation speed, the nth EO line will be drawn.

The Campbell diagram is Frequency vs. Speed. In order to interpret the chart correctly EO lines shall be superposed in the chart as shown in the Figure8. Resonance happens when the EO line collide with natural frequency of the turbine.

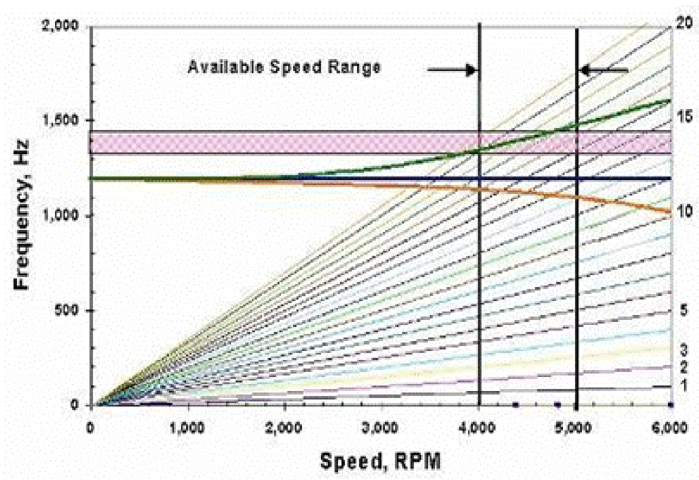


Figure 8- Campbell diagram-Courtesy of **KTH**

The most dangerous EO lines are first 4, i.e. 1,2,3 and 4 EO lines.

Another example of Campbell diagram is shown in figure 9

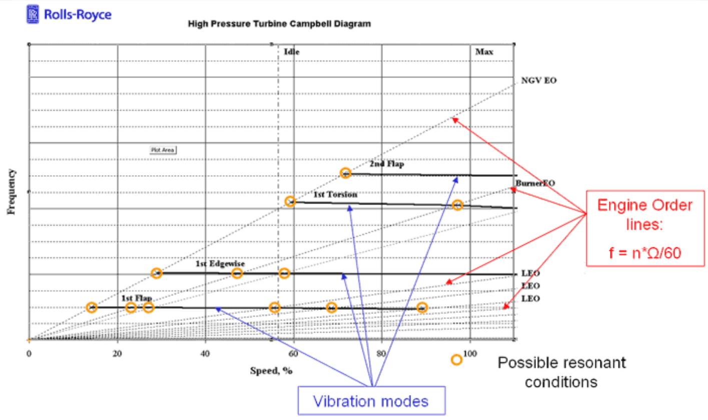


Figure 9- Another example of Campbell diagram- Courtesy of **KTH**

Exciting force generation phenomena

As mentioned earlier if blade frequency is equal to exciting frequency resonance will happen. But what will cause excitation?

The answer to previous question is steam flow. Steam flow in three cases can cause excitation in system. Steam flow can generate exciting forces by different methods. Major phenomena are listed here; however this list is not limited to items written here. Other parameters such as diaphragms design can also make exciting forces.

- Running speed: This type of excitation happens when steam pressure acting on a ring of blades are not equivalent. Meaning that first blade that face the nozzle ring will experience a pressure but as the rotor rotates, the next blade will experience not a same pressure. This phenomenon happens especially at the last stages where exhaust flange connects to turbine casing.
- Nozzle passing frequency: This excitation happens as the result of steam separation at trailing edge of nozzle vanes as the blade passes through.
- Partial admission: This type of excitation is similar to nozzle passing frequency, instead of a nozzle; a group of nozzles will cause the excitation force.
- Structure/foundation: Rotation of shaft will cause a vibration that is usually foreseen in turbine design (using Campbell diagram). However turbine

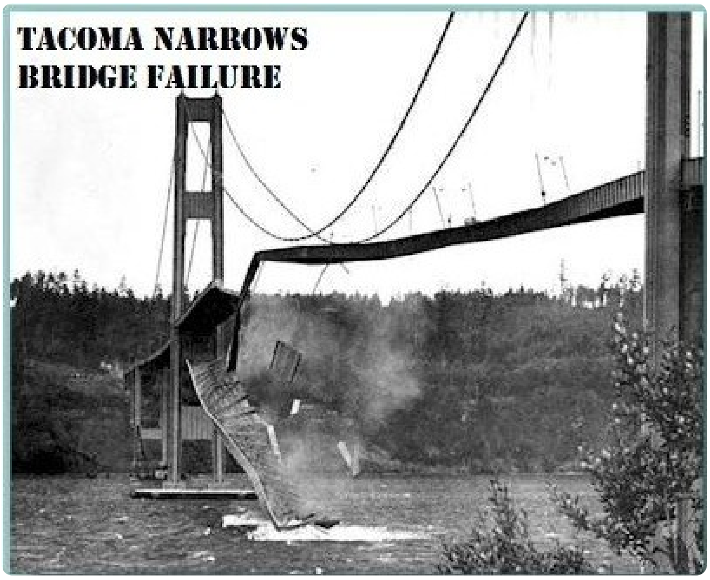
manufacturers usually do not design the support structures/foundation themselves. These vibrations can excite the structure if the frequency of vibrations is same as natural frequency of the structure.

- Casing Ribs: These ribs in the casing are manufactured for support reasons of casing. However, they can interfere with steam flow casing a wake like pattern that can induce the exciting force.

If it is certain that operating speed range contains one or more critical points according to Campbell diagram, the manufacturing features of the turbine train shall be changed in a manner that critical speeds are avoided.

Final word

Natural frequency excitation can create tremendous damages. An example from a bridge is shown in the figure 10.



> Figure 10- Bridge collapse due to excitation of its natural frequency- Courtesy of **Bright Hub Engineering**

This article is my interpretation on the book "Steam turbines: Design, Application and Re-Rating" By H.PBloch and M.P.Singh and KTH university (Stockholm-Sweden) Documentation. If you are eager to read more I highly recommend reading chapter 11 of the book or visit KTH university website, following the link I have provided in this article.

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References:

1. Heinz P. Bloch and Murari P. Singh, 2nd Edition. "Steam turbines: Design, Application and Re-Rating" Mc Graw Hill. 2009
2. **KTH university-Energy department documentations**
3. Cover Picture- Courtesy of **Researchgate**

#Campbell #Goodman #Soderberg #Vibration #Frequency #NaturalFrequency

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In this article two important diagram for analyzing the **#vibration** behavior of turbine blades discussed, **#Campbell** diagram and **#Goodman** diagram. Interpretation of these diagrams are vital, especially during the design of turbine blades, to avoid failure of blades.

Brian Deighton • 3rd+ 12mo
Rotating Equipment Specialist

glad I found this article. About to embark on a blade failure investigation

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with sharing and discusion to elavate the knowledge

Dear Amir Khodabandeh,I agree with Aref Hb comment relating your publishing share of knowledge,may I have more publishing share in gas turbine same as with steam turbine,because the specification of GT compared ST rather different.Tks and regard
sahat.hutagalung@energidutautama.co.id

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Especially about issue or topic as follow :"The metallurgical examination of a failed blade also corroborated High Cycle Fatigue failure probably due to the resonant excitation as a result of material loss near blade root. "

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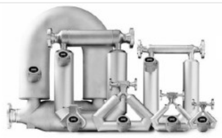

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