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Significance of synchronous amplification factor and its applications in turbine generator

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Abstract

The paper discusses the significance of Synchronous Amplification Factor (SAF) and its application in turbine generator. SAF is used to assess the rotating machines, how it behaves when passing through critical speeds or a balance resonance and also quantify the damping in the rotor bearing system to predict the forced vibration response at a resonance. Efforts have been made to describe the various graphical methods used in NTPC power stations for calculating SAF practically along with detailed interpretation. A few case-studies experienced by the authors are also described in detail. The acceptable criteria for assessing the well-designed and maintained rotor-bearing system are also included in this paper.

1 Introduction

The Synchronous Amplification Factor (SAF), Qs, is a commonly used measure of how a rotating machine behaves when passing through balance resonance and can be used to quantify the system damping in order to predict the forced vibration response at a resonance. It is usually measured using simple graphical methods on 1x filtered Bode and Polar Plots. However, the observed SAF can become difficult to interpret when split resonance exists in a machine. The paper explains the significance of SAF and its applications in turbine-generators. The practical determination of SAF is shown in a case study along with its acceptable criteria.

2 Significance of SAF

The Synchronous Amplification Factor SAF is measured by the ratio of the vibration amplitude at a balance resonance to the vibration amplitude at speeds well above the resonance. The "Amplification" refers to the fact that vibration is amplified when a vibrating system passes through a resonance. The term "Synchronous" refers to the fact that the vibration is the result of a rotating force (unbalance) which rotates at the same speed as (is synchronous with) the rotor. A machine with a large SAF will have a sharp, high amplitude balance resonance peak associated with a rapid change in phase. For example, a machine with an SAF of 10 would have a peak amplitude of vibration ten times the vibration levels at high speed, well above the resonance. Conversely, a machine with a small SAF will have relatively low maximum vibration amplitude at resonance, accompanied by a relatively slow change in phase.

SAF is often considered to be a measure of the damping of a machine, but, actually it is more complicated than that. The maximum amplitude of a rotor system at a balance resonance is controlled by the Quadrature Dynamic Stiffness of the machine. The Quadrature Dynamic Stiffness is a function of both the damping D, and the fluid circumferential Average Velocity ratio λ lambda. In machines with a significant amount of fluid circulation either as process fluid or in fluid-lubricated bearings or seals, the effective damping of the system is almost always significantly smaller than the value of D alone would indicate. Thus, it is more correct to say that SAF is a measure of the Quadrature Dynamic Stiffness of the rotor bearing system.

The dynamic stiffness is composed of two terms, a direct term and quadrature term. The direct term produces motion in-line with the force and contains a spring stiffness and mass stiffness component. The quadrature term produces motion at 90 degree to the force and contains the damping stiffness terms. At mechanical resonance, the spring stiffness and the inertial stiffness of the direct term are equal in magnitude but opposite in direction, so they cancel each other. At mechanical resonance, the only restraint is the Quadrature Dynamic Stiffness term. Thus the Synchronous Amplification Factor Qs, is a measure of the amount of Synchronous Quadrature Dynamic Stiffness that is present in the rotor bearing system at mechanical resonance. A high Qs indicates a low Synchronous Quadrature Dynamic Stiffness, and a low Qs indicates a high Synchronous Quadrature Dynamic stiffness which means sufficient damping.

3 Applications

SAF has become important in a machine acceptance testing. American Petroleum Institute (API) sets limits on the allowable maximum SAF for various machines. When these limits are incorporated into legal contracts between manufacturers and customers, the measurement of SAF can become important in satisfying the contractual requirements.

There are practical uses for SAF as well. Because the dominant vibration in most healthy machines is due to unbalance, a high SAF means that a relatively small unbalance can produce large amplitudes in the vicinity of a resonance. Thus, a machine with a high SAF might be more sensitive in the resonance region to changes in balance state for that mode. Also, machines which operate above a balance resonance needs to be able to get through the resonance without damage. A machinery with a large SAF could be vulnerable to rubbing while passing through a resonance during startup or shutdown. Thus, SAF can be used as rough guide for setting alarm limits when running above resonance.

4 Practical determination of SAF in turbine generators

There are three graphical methods which can be used to measure SAF; two of the methods use the amplitude part of a 1x rpm filtered Bode Plot and the third one uses a 1x filtered polar plot.

a) Half-power bandwidth method

b) Peak ratio method.

c) Phase slope method

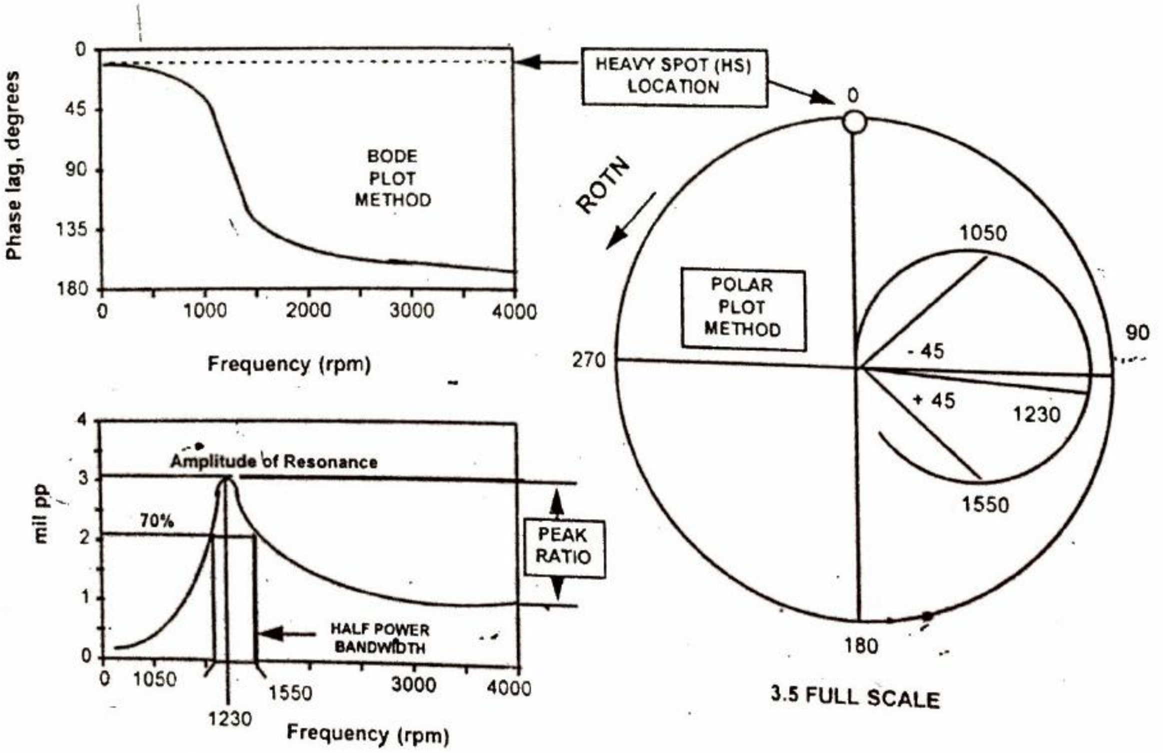


Fig. 1

4.1 Half power bandwidth method

The term Half Power Bandwidth method originated in AC electrical circuit theory, where the -0.3 dB point corresponds to a voltage oscillation amplitude of 0.707 times the amplitude at resonance. Since simple electrical and mechanical oscillators are mathematically equivalent, the method can be applied to rotor system, thus, the half power points of the Bode plot have a vibration amplitude of about 70% of the maximum balance resonance (critical) amplitude.

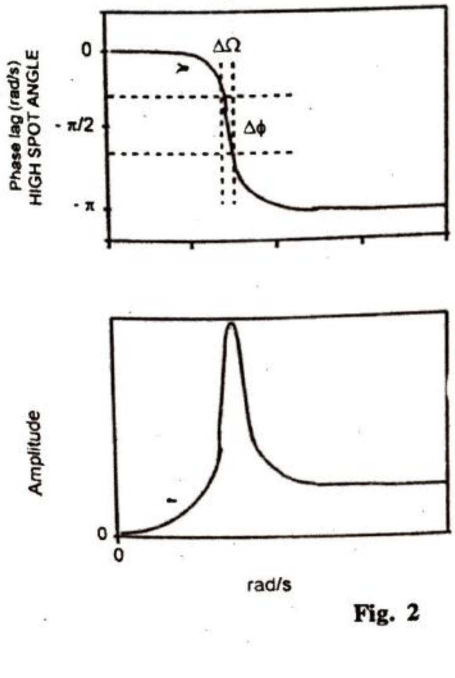
Once these two points have been identified, they are used to find the corresponding speed bandwidth. The difference between half power rotor speeds on each side of the resonance (Ω-high and Ω-slow) defines the Half Power Bandwidth. These two rotor speeds are used together with the speed of maximum amplitude (The resonance speed ΩRes) to calculate SAF:

$$\mathrm{SAF} = \frac{\Omega_{RES}}{\Omega_{HIGH} - \Omega_{LOW}} \quad ....(1)$$

4.2 The peak ratio method

The peak ratio method also uses the amplitude part of a 1x filtered Bode Plot. For an ideal rotor system, the ratio of the peak vibration amplitude at the balance resonance to the vibration amplitude at infinite running speed is equal to SAF. In practice, SAF can be measured by taking the peak vibration amplitude(A-peak) and dividing it by the vibration amplitude at a speed well above resonance (A-fast)

$$\mathrm{SAF} = \frac{\mathrm{Apeak}}{\mathrm{Afast}} \quad ....(2)$$



Rotor response with increased stiffness due to full annular rub

Fig. 2

4.3 Phase slope method

Finally, a third method can be used, based on a 1x rpm Filtered Polar Plot. For an ideal rotor system, half-power points have a phase of 45° ahead of and 45° behind the phase at resonance. To use this method, a line is drawn from the origin of a compensated polar plot to the maximum amplitude of the resonance. Then, two additional lines are drawn from the origin at 45° left and 45° right of the first line. The rotor speeds associated with these points are used in the same way as for the half-power bandwidth method.

$$\mathrm{SAF} = \frac{\Omega_{RES}}{\Omega_{+45^\circ} - \Omega_{-45^\circ}} \quad ....(3)$$

One good thing about these three methods is that the graphical measurements are independent of each other. Thus, they can be used as a check against mistakes in the calculation. Another thing to remember is that, because all real rotor systems deviate to some extent from the ideal, all three of these methods are approximate.

$$\mathrm{Qs} = \left(\frac{\Delta_\Phi}{\Delta_\Omega}\right)\left(\frac{\Omega_{RES}}{2}\right)$$

Several things can influence the accuracy of these measurements - uncompensated data, closely spaced shaft and casing modes, and split resonances. All plots must be compensated for slow roll runout before attempting the calculations. Closely spaced modes especially affect the Peak Ratio Method, where the "high speed" response may be covered up by a higher mode or a mode from an adjacent machine. Split resonance can make the measurement of SAF both difficult and dependent on angular orientation of the transducer used to measure the vibration.

A QS value calculated from Bode Plot should agree with that calculated from a Polar Plot. Small differences are normal, and are due to accuracy in

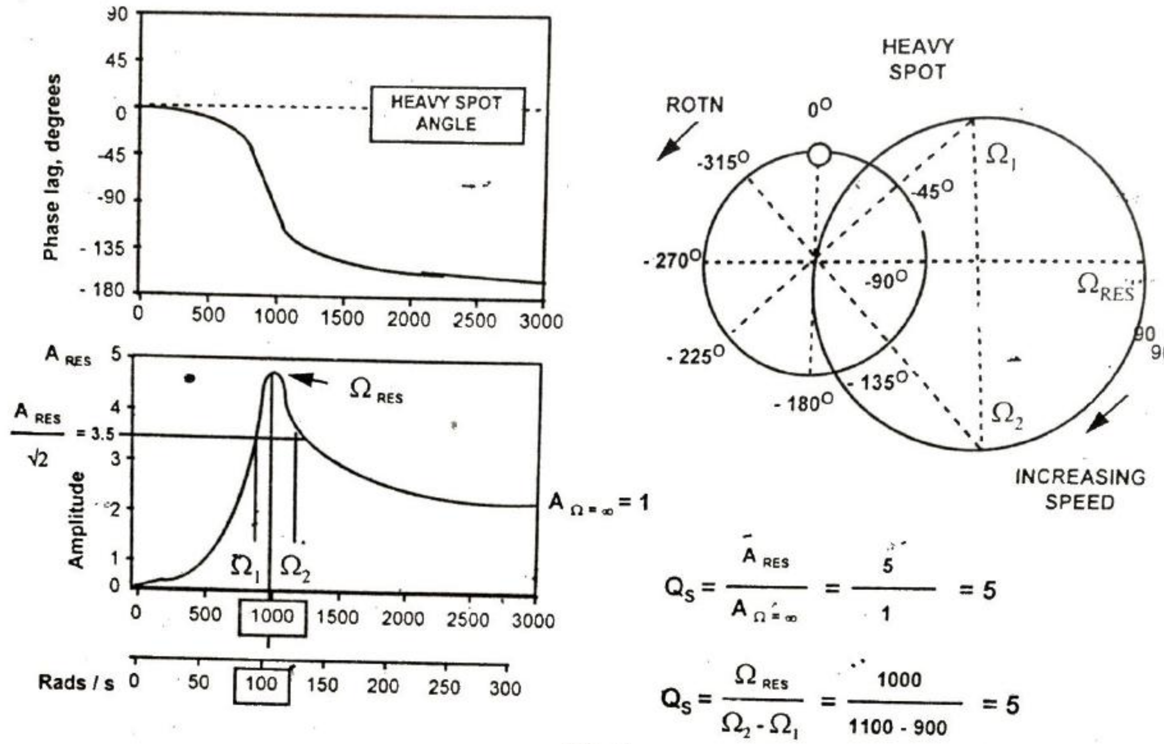


Fig. 3

determining values. However, a Qs calculated from startup data and a Qs calculated from rundown data, may also differ due to thermal load and for other reasons. Caution should be used when applying Qs by either the Half-power-Bandwidth method or the Amplitude Ratio method, because of potential mechanical non-linearity and abnormalities which can affect machinery vibration response; further the Synchronous Amplification Factor does not define or describe the properties that determine rotor stability.

5 Practical determination of SAF with a case study

5.1 Case study : Talchar TPS 60 MW

The TTPS unit #2 comprises of four sleeve lubricated bearings commissioned two decades ago. The bearing no.2 had high vibration since replacement of bearing no.3 and no.4 which were found damaged in the last shutdown. Machine was re-synchronized and observed that bearing no.2 vibration level is crossing 45 μm pk-pk beyond 27 MW load. Corporate expert team was called in to investigate the problem, as the site could not load the machine more than 27 MW. When loaded beyond 27 MW, the vibration level increases above 150 μm. The turbine rear bearing no.2 vibration behaviour was studied in two modes Steady state and rundown.

a) Rundown Behavior

Mechanical rundown of bearing no 2 and shaft vibration was taken and found that the critical speed amplitude was of the order of 175 μm pk-pk at 1673 rpm on the bearing vertical and 350 shaft vibration in mm 0-peak at 1371 rpm measured by non-contact pickups mounted 90° apart.

Observations:

1) Bearing no.2 vibration was observed to be high and was unacceptable after 27 MW load.

2) Shaft vibration was also very high, maximum 350 mm 0-peak, is also not acceptable at critical.

3) SAF was calculated and found to be very high, more than 8, which indicates low quadrature dynamic stiffness, insufficient damping.

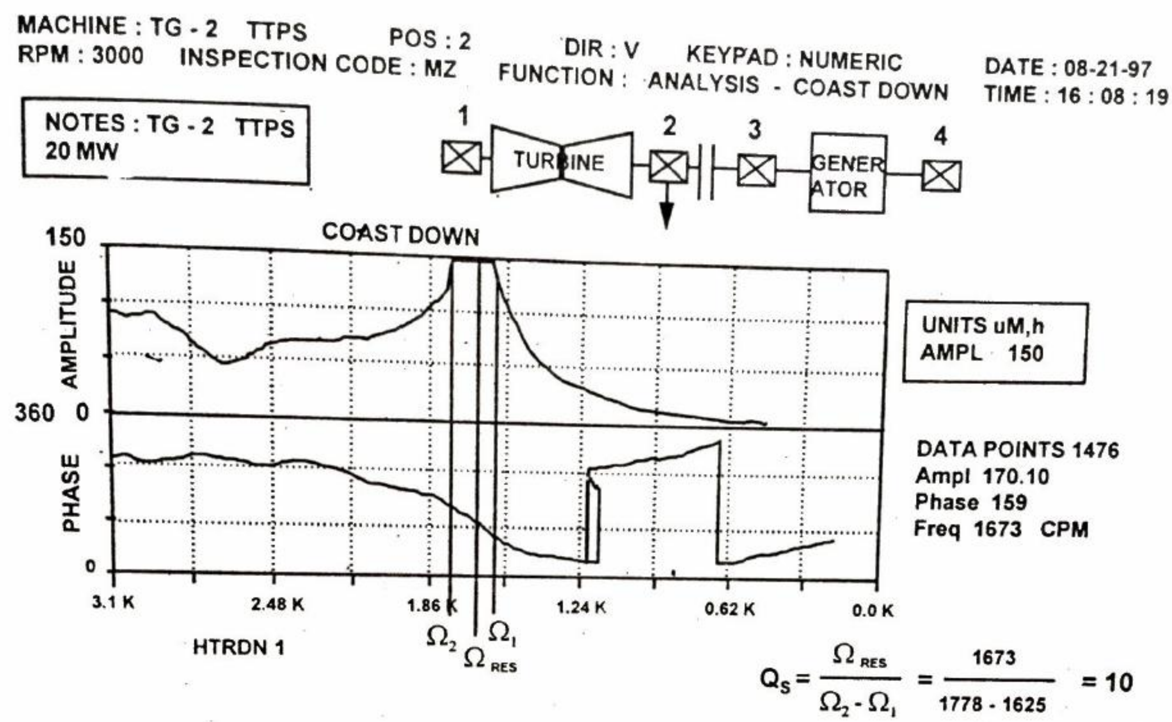


Fig. 4

b) Steady state behaviour

The shaft vibration behaviour was observed by shaft centerline plot which revealed that the shaft average centerline was very close to the bearing clearance at the upper left quadrant in the bearing, after increasing the load beyond 27 MW. 'The shaft average centerline got shifted to the bearing geometrical center' means a force which has shifted the rotor could be due to rubbing and catenary disturbance /bearing damage.

c) Calculation of SAF using bearing vibration

Coast-down signature, so called Bode plot, was taken and found that critical speed amplitude is very high and also noticed changes in critical speed values. SAF was calculated to know whether the bearing has sufficient damping or not.

$$SAF = \frac{\Omega_{RES}}{\Omega_{HIGH} - \Omega_{LOW}} = \frac{1673}{1778 - 1625} = 10$$

High SAF value is an indication of insufficient damping and rubbing. Machine is under shutdown for inspection.

6 Acceptable criteria for SAF

The general guidelines for evaluation of damping in the rotor-bearing system are as follows.

SAF	Remarks
$Qs < 5$	Exceptionally well designed system and having sufficient damping
$Qs \geq 5 - 8$	Marginal damping at resonance
$Qs > 8$	The system has low Quadrature stiffness at resonance.

7 Advantages

i) Calculation of SAF is a measure of system damping.

ii) Low SAF is an indication of healthy machine

iii) High SAF will be an indication of improper damping

8 Conclusions

The finding of the case study and calculated value of SAF leads the authors to conclude that the machine/rotor-bearing system with high SAF should not be allowed for operation. It needs investigation and necessary remedial before machine the gets damaged.

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