Hot Spot Stability Analysis for Rotors with Brush Seals

In version 4.2 the hot spot stability analysis has been introduced (also see release notes http://www.delta-js.ch/file/344/MADYN_2000_Release_42_rev1.pdf). In version 4.3 it has been further extended. Hot spots can now also be modelled at locations with a flexible stator. All flexible stator models (SBS, DBS) are supported.

In the following we would like to demonstrate a hot spot stability analysis with hot spots caused by brush seals. Brush seals are relatively new and it is known, that one must be careful when applying them, since they can cause hot spots, which lead to high vibrations in case of instability.

MADYN 2000 allows modelling virtually any hot spot mechanism, among others hot spots caused by brush seals. Shaft trains with simultaneous considerations of 38 brush seals have been analysed. The example presented here is an industrial steam turbine with 3 brush seals.

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1. Description of the System

1.1 Rotor Bearing System

The rotor can be seen in figure 1.1. The rotor is supported on two fluid film tilting pad bearings with load on pad as shown in figure 1.2. The bearing support is a spring damper system. Its data are shown in figure 1.1. The hot spot locations are indicated by the dark red flash.

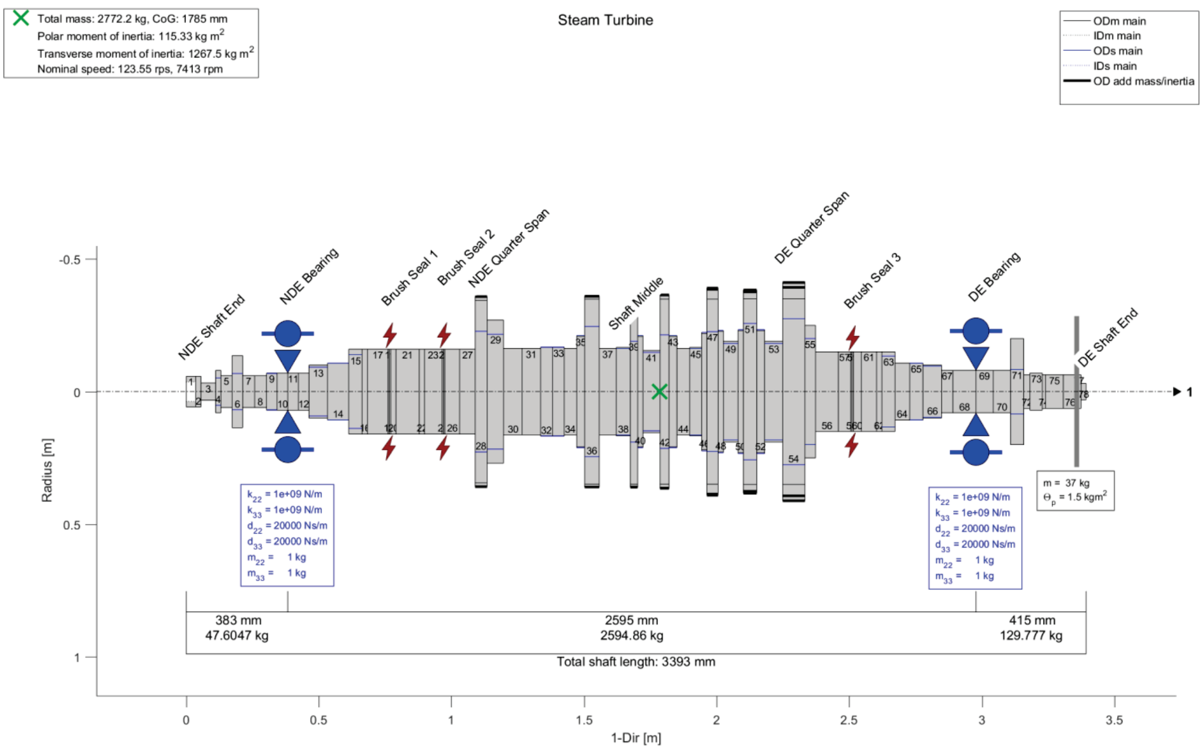

Fig. 1.1: Rotor model with support data

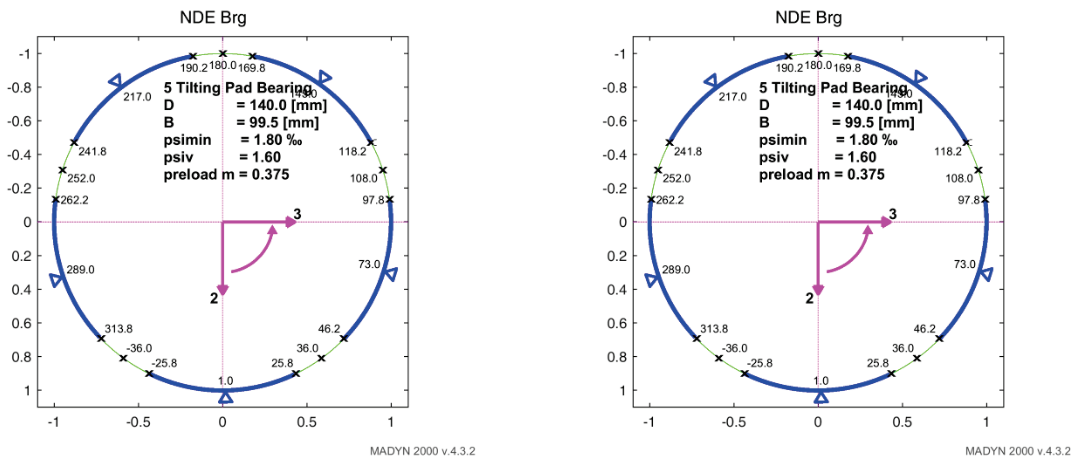

Fig. 1.2: Fluid film bearings

1.2 Hot Spot Model of the Brush Seal

For the hot spot at the brush seals is assumed, that the hot spot arises in direction of a vibration proportional to the contact stiffness of the brush seals. The heating model according to Kellenberger is applied:

$$\dot{x_T} = p\Omega x - q x_T \quad (1)$$

with x as the displacement at the hot spot location, x_T as the thermal deflection at some reference point and Ω as the rotor speed.

More details are explained in the documentation in chapter II.15.1, in the release notes http://www.delta-js.ch/file/344/MADYN_2000_Release_42_rev1.pdf and in papers on our website http://www.delta-js.ch/en/downloads/technical-papers/hot-spot-stability/.

For the factors p and q for the added and eliminated heat formulas are derived in the MADYN 2000 documentation in chapter VIII.3. They are as follows:

$$q = \frac{3\alpha A}{mc} \quad (2)$$

$$\frac{p\,\Omega}{q} = \frac{\pi\, k\, \mu\, u\, \beta}{2\, \alpha\, A} \quad (3)$$

α as the heat transfer coefficient on the rotor surface,
A as the surface area along the length subject to a temperature difference,
m as the mass of the journal along the length subject to a temperature increase,
c as the specific heat capacity of the shaft material,
k as the contact stiffness,
μ as the friction coefficient,
u as the circumferential speed and
β as the ratio of the thermal deflection to the cross sectional temperature difference.

Some of the parameters such as the stiffness of the brush seals influenced by the friction between the bristles or the friction coefficient between brush and shaft surface are uncertain, which limits the accuracy of the model. Nevertheless the hot spot stability analysis will be able to clearly indicate dangerous speed ranges, although it will not be possible tell with 100% certainty, whether the system is stable or not.

In the current example the factors p and q for the added and eliminated heat are as follows

p = 50 for β = 1m/K

q = 0.01 1/s

The actual β value is automatically calculated at the hot spot location as reference point from the thermal deformation for 1°C cross sectional temperature difference along the length of the brush seal.[1] The thermal deformation for the 3rd hot spot can be seen in figure 1.3. The displacement at the hot spot is highlighted.

[1] Note, that the length subject to the cross sectional temperature difference is an input value to the hot spot. It can be adjusted to results of measurements or a 3D finite element analysis.

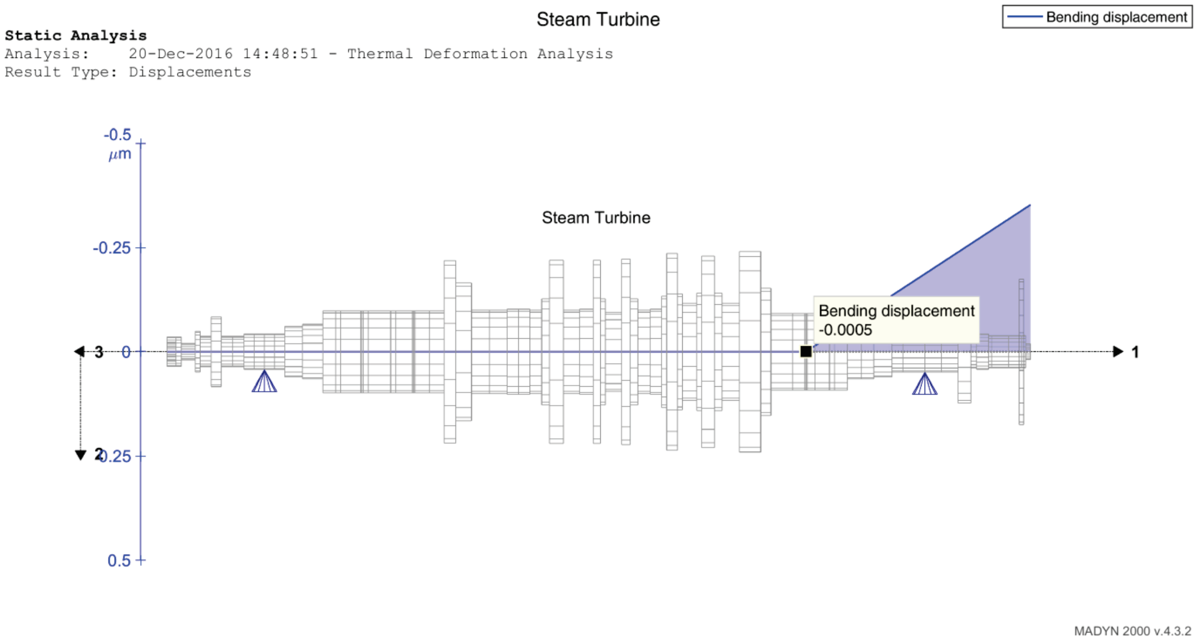

Fig. 1.3: Thermal deformation for the cross sectional temperature difference at the 3rd hot spot

2. Natural Modes of the System, Campbell Diagram

The Campbell diagram of the system is shown in figure 2.1 and the modes in the critical speeds in figure 2.2. These results will help to better understand the results of the hot spot stability.

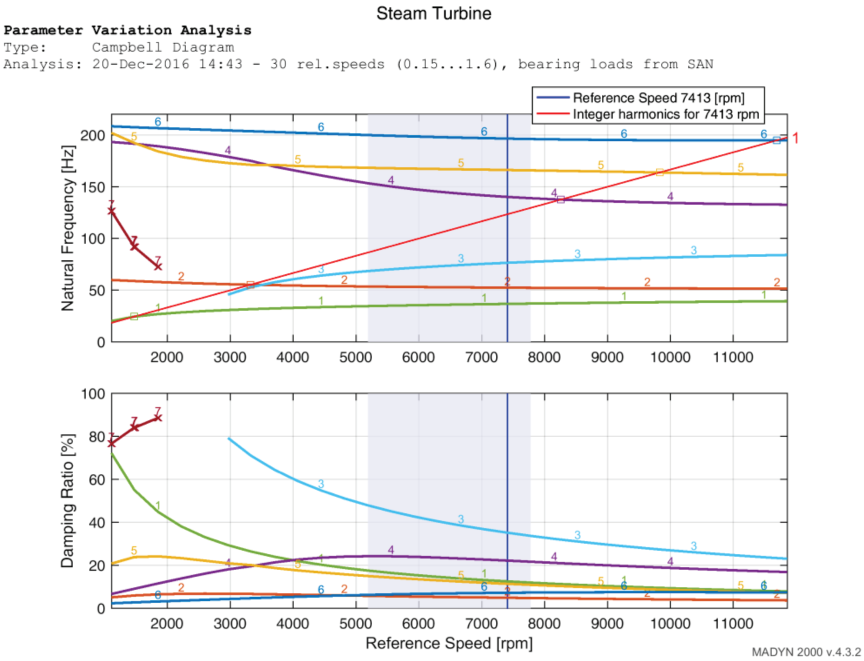

Fig. 2.1: Campbell diagram

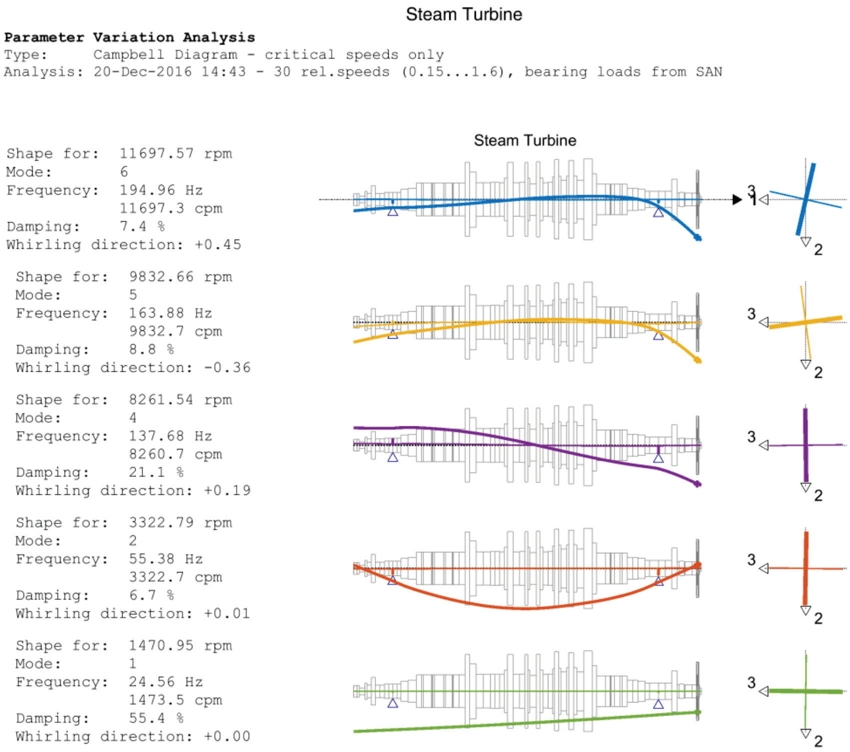

Fig. 2.2: Modes in the critical speeds

3. Hot Spot Stability

Eigenvalue results of the 3 hot spot modes caused by the 3 hot spots are shown in figure 3.1. The modes at a speed of 7’413 rpm can be seen in figure 3.2. They represent the response to the thermally bent shaft. All eigenvalues have a negative real part, so the system is stable. The 2nd hot spot mode has the largest real part at operating speed and the 3rd mode close to 3’000rpm. Both speeds are close to criticals, which are indicated by the black vertical lines. The imaginary part of the eigenvalue indicates the frequency of the hot spot in a fixed coordinate system. The difference to the rotor speed, which is shown in figure 3.1, is the frequency of the hot spot for one revolution on the shaft surface. A positive frequency means the rotation is in the same direction as the shaft rotation, a negative frequency in the opposite direction.

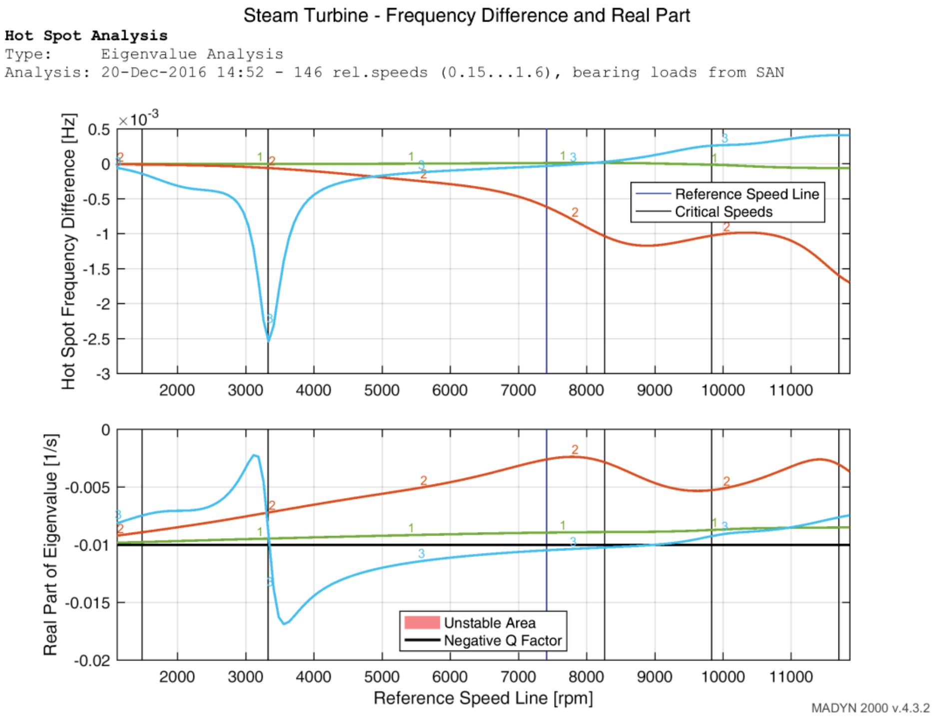

Fig. 3.1: Eigenvalue of the hot spot modes

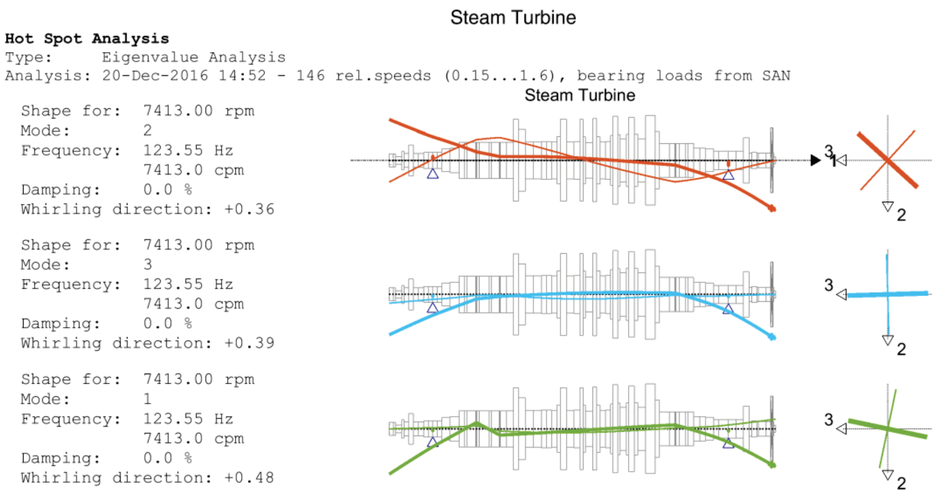

Fig. 3.2: Hot spot modes at 7’413 rpm

The hot spot stability threshold can be shown as heat ratio of the added to eliminated heat as in figure 3.3. This presentation is only possible, if all hot spots have approximately the same p and q values. Since the system is stable the threshold is above the actual heat ratio.

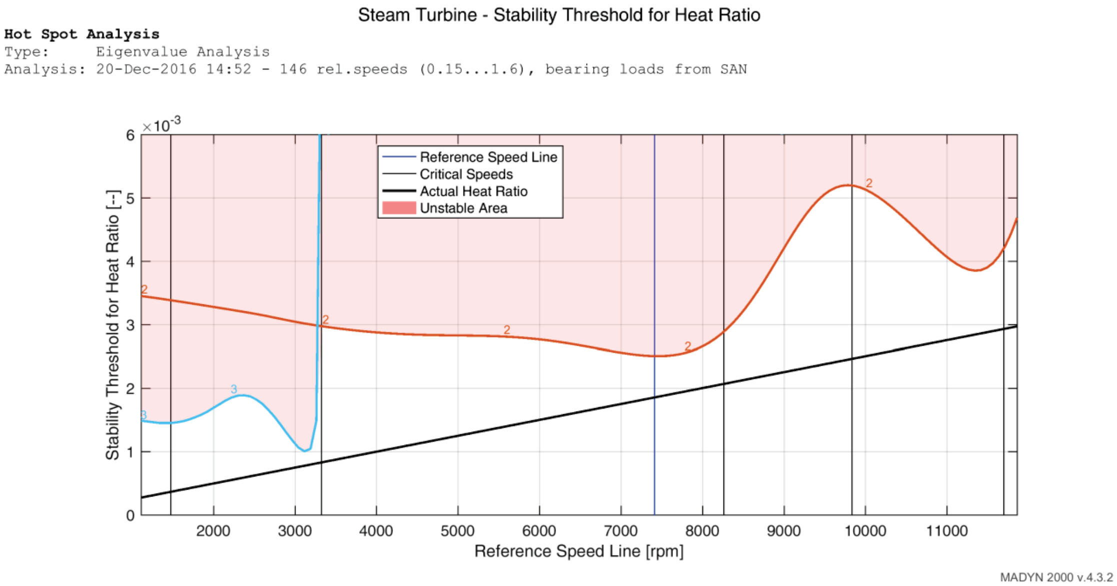

Fig. 3.3: Stability threshold for the heat ratio $\frac{p\Omega}{q}$

Alternatively the threshold can be shown as a factor, by which the lowest heat ratio must be multiplied to reach the threshold (see figure 3.4). This presentation can always be applied, even if each hot spot has different p and q values. Since the system is stable the factors in figure 3.4 are larger than 100%.

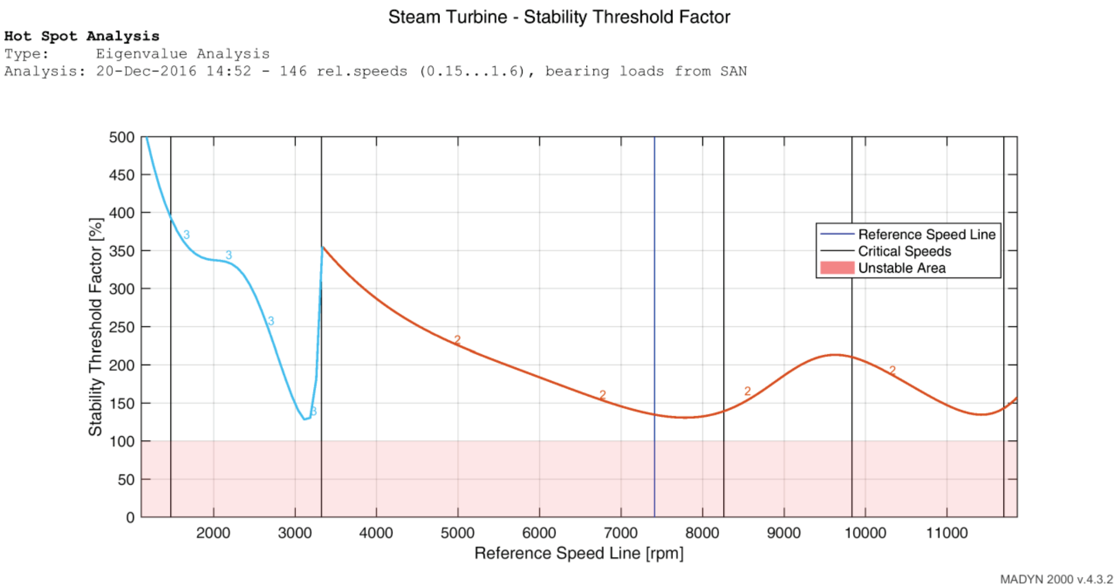

Fig. 3.4: Stability threshold factor

Although the system is stable it can be seen in the diagrams in figure 3. and figure 3.4, that the margin is not big at certain speeds. There is a low margin at about 3'000rpm which is caused by the 1st vertical bending mode of the turbine (see Campbell diagram and mode shape in figure 2.1 and 2.2). There is also a low margin close to operating speed, which is caused by the horizontal tilting mode (also see figure 2.1 and 2.2).

4. Conclusions

The hot spot stability of an industrial steam turbine with 3 brush seals has been analysed. Although the modelling of the brush seals is subject to uncertainties such as friction coefficients and stiffness values, it was shown, that such an analysis can quickly and easily reveal dangerous zones for an unstable hot spot caused by the brush seals.

In the present rather simple system the dangerous zones are close to critical speeds. In more complex systems such as power generation shaft trains consisting of several rigidly coupled turbines and a generator the modes and the interpretation of dangerous zones is more complex. The analysis is also proven for such systems. Systems with up to 38 brush seals were analysed.