Beam mode core-barrel vibrations in the PWRs Ringhals 2-4

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Abstract

Analysis of core-barrel vibrations in the Swedish Ringhals PWRs has been performed by Chalmers since the early 1990's. In the first phase of this work, between 1991 and 1998, the evaluation method has been developed such that it made a consistent comparison between different measurements possible. A trend analysis showed that the beam mode amplitudes have steadily increased between 1991 and 1998 in all three plants.

This paper is to report on the second phase of the work, performed during 2005, on measurements made both before and after the summer outage 2005 in all three plants. During the summer outage, the hold-down spring in Ringhals-3 was replaced. The analysis shows that the vibration amplitudes increased in an accelerated rate between 1998 and 2005 in all three plants. In Ringhals 3, however, after the change of the hold-down spring, the beam mode amplitude has reverted to close its original level of 1991.

It became also clear that the extraction of the information from the vibration peaks needs to be refined and made less subjective. A new method of algorithmic peak separation was elaborated, which supplies more information than the previous analysis; it gives also the peak width in addition to peak amplitude and peak frequency, while also supplying more accurate estimates for the latter two.

KEYWORDS: core-barrel vibrations, beam mode, peak estimation, trend analysis

1. Introduction

In order to monitor the flow induced beam-mode core-barrel vibrations in a Pressurised Water Reactor, PWR, it is possible to use the ex-core detector signals [1]-[3]. From the Auto- and Cross-Power Spectral Densities (APSD and CPSD) of such signals, it is possible to gain knowledge about the vibration frequency and its relative amplitude. It could also be possible to calculate the absolute amplitude of the vibration but this has not been done in the present paper. It is especially important to monitor the change of the vibrations due to the power up-rate (increasing power and hence core flow), which is taking place in Sweden at the moment. It is also of interest to monitor the vibrations during a longer time period and make a trend analysis in order to determine the possibility of material fatigue and wear. Previously, a trend analysis was

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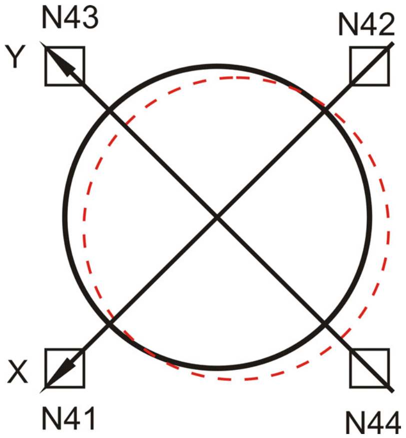
performed on measurements made during 1991-98 at the Swedish NPP Ringhals, but no new measurements were made since then until recently. Therefore, new measurement where taken during 2005 at all three PWR-units at Ringhals.

The work in this paper has three different objectives. The first objective is to compare the results of the recent analysis of the vibrations with those taken in the period 1991-98 [4]-[5], in order to follow up the development of the vibration characteristics in form of a trend analysis. The trend analysis will also be important in the future to monitor the change of vibrations due to the planned power up-rate in Ringhals 2-4. The results from the present analysis were compared to the previous results. The second objective is to investigate the changes of the properties of the core-barrel vibrations before and after the outage in the summer of 2005 in Ringhals-3. During the outage the hold-down springs were replaced to decrease the vibration amplitude. Thirdly a curve-fitting procedure was developed to better extract the information from the vibration peak by removing the influence of the background of the APSD. The curve-fitting also allows us to calculate the width of the peak which will give another parameter that can be used for characterizing material conditions.

2. Model of the induced noise

There are different vibration modes of the core-barrel as with every mechanical system. In the case with a core-barrel in PWR:s two vibration modes are of special interest, namely the first vibration mode, i.e. the beam-mode, and the second mode, which is called the shell-mode. In this paper we focus our attention on the first mode which is illustrated by the dashed circle in Fig.1. The beam-mode is also called the pendulum-mode since it executes a pendulum-like motion.

Figure 1 Positions of the ex-core detectors relative to the core.



The different vibration modes of the core-barrel induce neutron noise, which can be monitored by the ex-core detectors. It is possible to separate the different modes by adding and subtracting the signals from the different detectors, since the modes have different symmetry properties. The beam-mode vibration has a 180^o rotational symmetry whereas the shell-mode has 90^o rotational symmetry. In Ref. 4 the following expressions were derived for the *x* and *y* components of the ex-core noise induced by the beam-mode vibrations:

$$\mu x(t) = \frac{1}{2}[\delta\phi_1(t) - \delta\phi_2(t)],$$
$$\mu y(t) = \frac{1}{2}[\delta\phi_3(t) - \delta\phi_4(t)]. \qquad (1)$$

where the induced neutron noise, $\delta\phi_n(t)$, is measured at detector *N4n, n*=1..4, respectively. Then by using the so-called *k-α model* for 2-D random anisotropic vibrations, it is possible to write the auto-spectra, S_{xx} and S_{yy}, of the x and y component as:

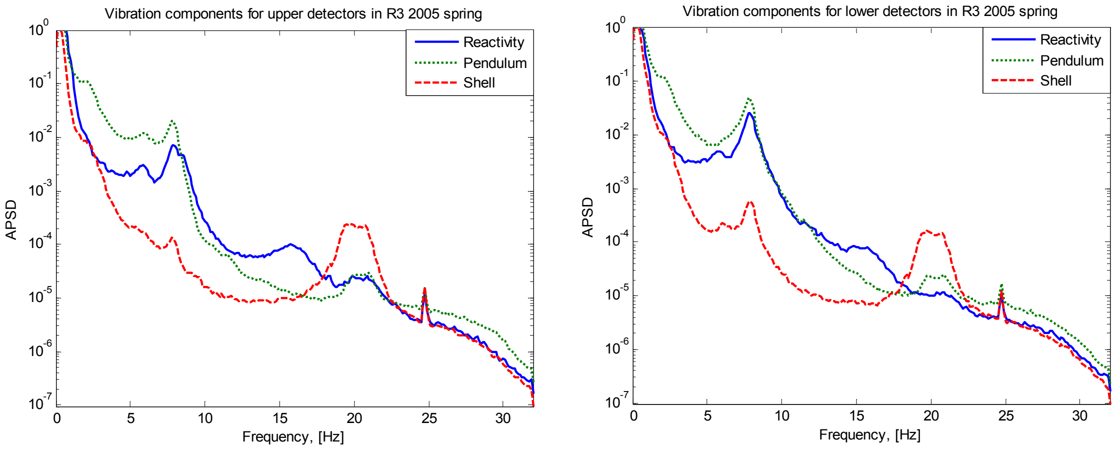
$$S_{xx}(f) = |S(f)|^2\,(1 + k\cos 2\alpha),$$
$$S_{yy}(f) = |S(f)|^2\,(1 - k\cos 2\alpha). \qquad (2)$$

Hence, it is possible to write the spectra, $S(f)$ of the beam-mode vibration as:

$$APSD_{beam} = \frac{S_{xx}(f) + S_{yy}(f)}{2} = |S(f)|^2 . \qquad (3)$$

In Fig. 2 the spectra of the different vibration components are shown. It is clearly visible that the beam-mode has an eigenfrequency at around 8 Hz and it is separated from the shell-mode vibration which is at 20 Hz.

Figure 2: Spectra of the different components in the ex-core detectors.



3. Parameter estimation

In order to monitor the beam-mode vibration one can estimate the peak value and eigenfrequency of the peak from the APSD given in Fig. 2 This is also the procedure that was followed in the past for measurements made between 1991 and 1998 at Ringhals 2-4, [4]-[5]. The results from this analysis showed that the amplitude of the vibration peak had increased but the eigenfrequency remained roughly the same. In this paper we have continued the analysis by including measurements form 2005 for all three units. The estimation of the peak parameters were done in the same way as earlier. The results from this analysis are presented in the section

Trend analysis below. However, it also is also possible to make a better estimation of the peak parameters by using curve-fitting procedures which will be described in the next chapter.

4. Curve-fitting

In order to improve the estimation of vibration peaks in the spectra of the ex-core detectors, it is possible to use curve-fitting procedures. We start by assuming that the mechanical vibrations can be represented as the oscillations of a linear damped oscillator, driven by a white noise force, *F(t)*. Then the time-dependent equation for the induced noise, $\delta\phi(t)$ can be written as

$$\delta\ddot{\phi}(t) + 2D\omega_0\delta\dot{\phi}(t) + \omega_0^2\delta\phi(t) = F(t). \qquad (4)$$

From this it is possible to turn to the frequency domain by making a Fourier transformation and utilising $\omega = 2\pi f$ and rescaling $F(f)$ with $1/(2\pi)^2$:

$$\delta\phi(f) = \frac{F(f)}{-f^2 + 2iDf_0 f + f_0^2} = H(f)F(f). \qquad (5)$$

Finally, the Wiener-Khinchin theorem is used and the fact that the APSD from a white noise is a constant, [6]. Then one ends up with the following expression for the noise:

$$APSD_{\delta\phi}(f) = APSD_F(f)\left|H(f)\right|^2 = \frac{C^2}{(f^2 - f_0^2)^2 + 4D^2 f^2 f_0^2}. \qquad (6)$$

Here, f_0 is the eigenfrequency, D is the damping coefficient and C^2 is a parameter proportional to the vibration amplitude. By calculating $APSD_{\delta\phi}(f)$ using (1)-(3) from the measured signals, it is possible to fit the measured data to (6) with three unknown parameters *C*, *D* and f_0. The fitting is done by using MatLab [7], with a least-square fitting algorithm. However, inspection of the measured spectra (c.f. Fig. 2) shows that the peaks are superimposed on a background that decreases with increasing frequency quite markedly. Hence one can expect to get a better estimate of the parameters if the actual fitting is done to the following equation:

$$APSD_{\delta\phi}(f) = \frac{\tilde{C}}{f^2 + \tilde{D}(f^2 - f_0^2)^2} + A_1 f + A_2. \quad (7)$$

Here the two last terms on the r. h. s. are a simple linear term and a constant background, respectively. The following connections between the estimated parameters and the search parameters hold:

$$D^2 = \frac{1}{4\tilde{D}f_0^2}, \qquad C^2 = \frac{\tilde{C}}{\tilde{D}}. \qquad (8)$$

Initial values for the parameters to be estimated by the least-square fitting algorithm have to be given as inputs, Therefore, initial guesses of the amplitude, the full-width at half maximum (FWHM) and frequency of the peak is manually estimated from the APSD. From these parameters estimations of initial values for $\tilde{C}$, $\tilde{D}$ and f_0 can be calculated. Also the frequency-range is given manually to the algorithm for each measurement, normally between 4 to

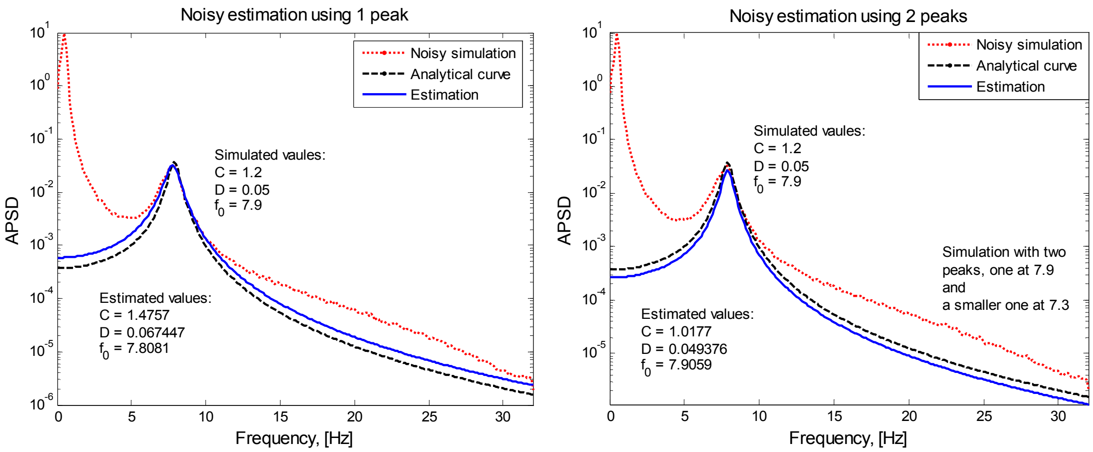
10 Hz. Once the parameters have been estimated it is possible to calculate the peak frequency, f_{peak}, the FWHM and the peak height, A_{peak}, according to the following expressions:

$$
\begin{aligned}
f_{peak} &= \sqrt{f_0^2(1-2D^2)}, \\
f_{FWHM} &= f_0\sqrt{(1-2D^2) \pm 2D\sqrt{1-D^2}}, \\
FWHM &= \Delta f_{FWHM}, \\
A_{peak} &= \frac{C^2}{4f_0^4 D^2(1-D^2)}.
\end{aligned}
\tag{9}
$$

4.1. Simulations

A good practice to obtain an algorithm working satisfactorily is to test it on known data. Hence, the curve-fitting procedures are first tested on simulated signals corresponding to some realistic values of the parameters in (4). In simulations, it is also possible to investigate how a second peak with much lower amplitude but almost the same frequency as the beam-mode peak will influence the estimation of the parameters. It is also possible to investigate the influence of "noise" added to the signal spectra. In the left plot in Fig. 3 a simulated signal with some noise (dotted curve) is shown, corresponding to two vibrations, one with high amplitude which represents the beam-mode vibration and one with lower amplitude representing some other type of hypothetical vibration. The introduction of a second peak is prompted by observations of the spectra from the measurements. The curve for the beam-mode vibration is also shown as a dashed curve. In the right of Fig. 3 the solid curve is the fitted curve corresponding to the beam-mode vibration when two curves are used in the fitting algorithm, whereas to the left in Fig. 3 only one curve is used. The estimated values are also shown in the figures and as can be seen, the case with two fitted curves is much better at estimating the correct parameter values.

Figure 3 Simulation of the beam-mode vibration with noise and another peak close. To the right two curves are used in the estimation and to the left only one.

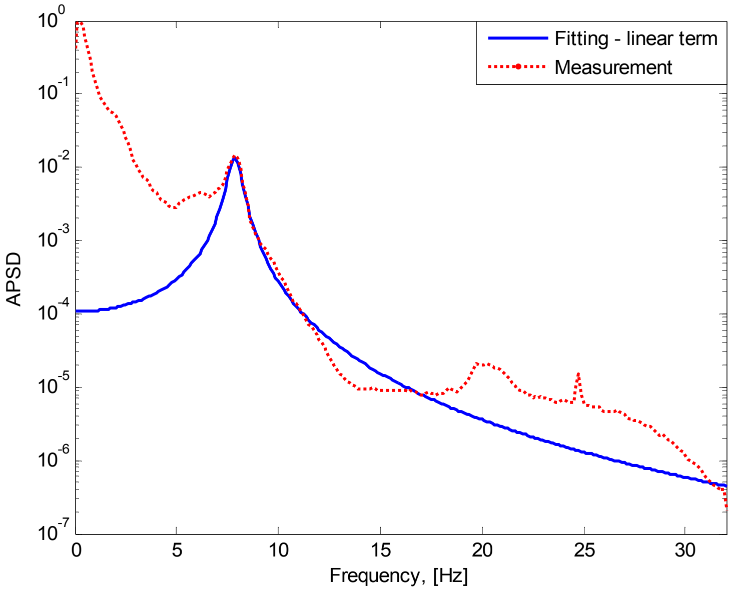


4.2. Measurements

In reality there are several peaks present in the spectrum, even if some of the peaks are removed by the adding and subtracting of the signals using equations (1)-(3). However, some peaks that are not due to the beam-mode core-barrel vibrations may remain in the spectra. Especially there may be a peak close the beam-mode peak which corresponds to the fuel assembly vibrations, [8]. Sometimes this second peak is visible and sometimes one can only see a broad single peak, due to two superimposed peaks. Hence, the best estimation of the beam-mode peak will be achieved if the broad peak is assumed to consist of two peaks. Then estimation to these two peaks can be made. One also has to consider the possibility of a superimposed background. If a linear trend is added to the fitting, as in (7), it is possible to estimate the parameters of the peak by eliminating the effect of the background.

This procedure was applied to the present measurements with good results. As an illustration, in Fig. 4 an APSD from the lower ex-core detectors in Ringhals-3 is shown together with the estimated peak.

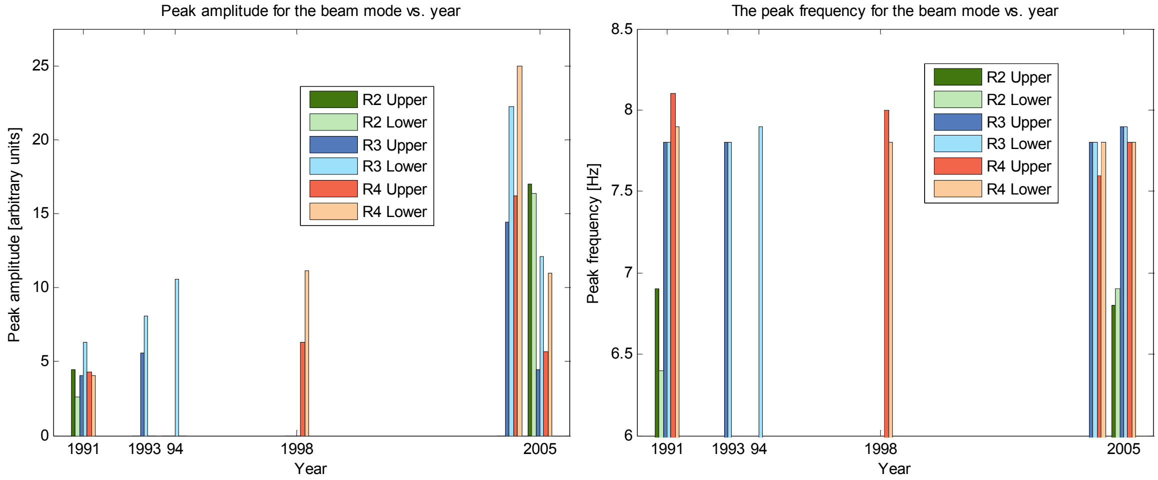
Figure 4 APSD of lower ex-core detector signals from R3 with fitted curve without linear background term. Measurement made in autumn 2005.



5. Trend Analysis

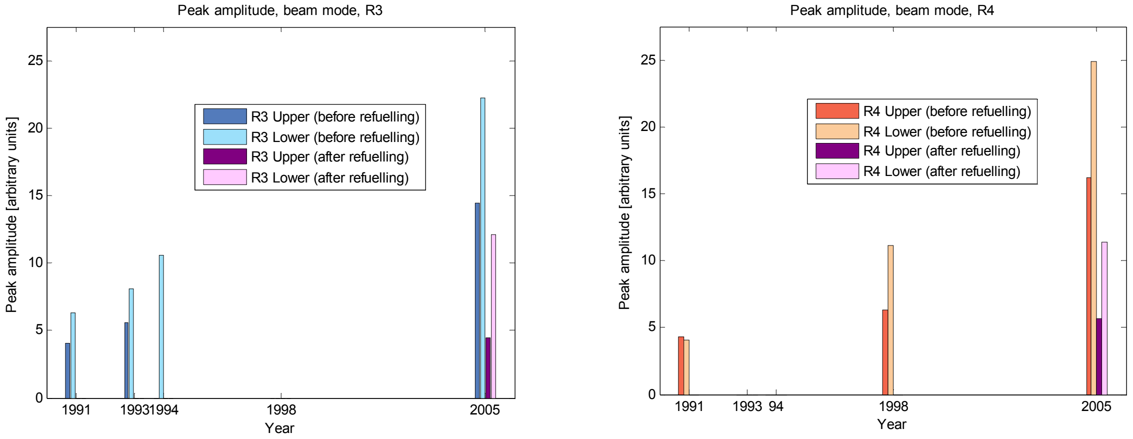
The trend analysis is based on both the manual “peak” method and the curve-fitting method. In the following figures the results from both analyses are presented. In Fig. 5 the result from the “peak” method trend analysis of the vibration amplitude is shown beginning at the year of 1991.

Figure 5: Trend of the vibration peak amplitude and frequency.



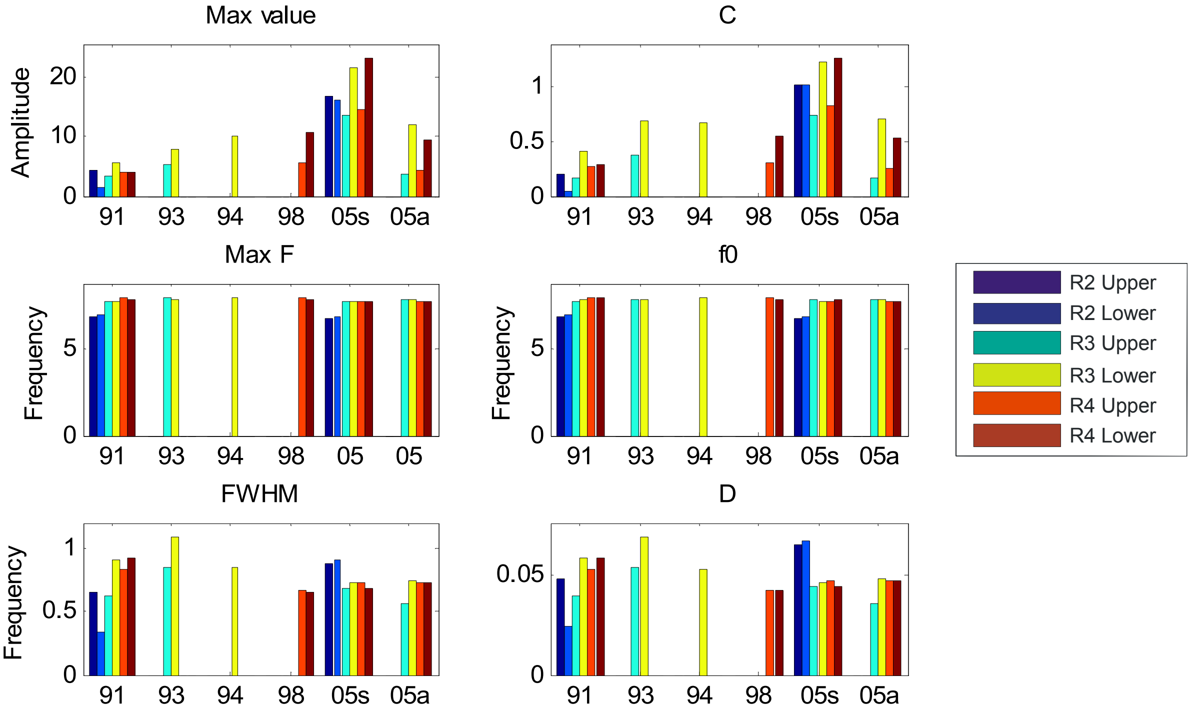
To make a more detailed analysis, the results before and after the re-fuelling in 2005 are shown in Fig. 6. Here it is clearly visible that the amplitude is decreasing in both Ringhals-3 and Ringhals-4.

Figure 6: Amplitude before and after revision.



The results from the curve-fitting analysis are shown in Fig. 7. There is good agreement between the two methods. It is also seen from the lowermost part of Fig. 7 that the additional information of the width, *D*, of the peaks does not seem to give any further information about the vibration properties.

Figure 7: Estimation of parameters from curve-fitting. 05s stands for 2005 spring and 05a stands for 2005 autumn.



6. Conclusions

The following conclusions can be made from the trend analysis given in the foregoing.

- The vibration amplitudes have increased for the beam mode (pendulum) for all units as compared to the previous values. The rate of increase appears to be somewhat faster for the period 1998-2005 than for the previous period, i.e. 1991-1998, and are about a factor 3 to 4 higher than in 1991;

- in general, the vibration frequency has decreased slightly for all reactor units. This change is not faster than in the previous period, and moreover it shows some statistical scatter, i.e. the trend is not completely monotonic. Nevertheless, it points into the same direction as the amplitude, i.e. it reflects a slight general weakening of the integrity of the core-barrel system against flow induced vibrations;

- the amplitude of the beam mode vibrations decreased significantly (by more than a factor 2) in R3 after refueling with the change of the hold down springs, compared to their values before re-fuelling. The amplitude values got down to a level comparable with those in the earliest measurements available to us, i.e. from 1991. Hence, it is possible to see the effect of the change of the hold down springs by monitoring the beam mode vibrations. However, the amplitude for

Ringhals-4 is also showing the same kind of behaviour. This is unexpected since there was no change of hold-down springs in this unit. The reasons for this change are not understood at the moment, and further measurements will be necessary to clarify the reason.

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