Operational Modal Analysis of Large 2-pole Rotating Machinery

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ABSTRACT: Operational Modal Analysis (OMA) is increasingly used for analyzing structural properties of rotating machinery. Until a few years ago, the presence of dominant harmonic components would limit the useful frequency range, but today methods exist to automatically detect and subsequently eliminate their influence. This paper concerns OMA on large 2-pole rotating machinery. The analysis has been limited to the frequency range around 50 and 100 Hz, where unbalance and electromagnetic forces, respectively, can give high vibration amplitudes of the stator. Two methods have been used for the analysis: Curve-fitted Frequency Domain Decomposition (CFDD) and Stochastic Subspace Identification (SSI). The methods are evaluated and the results are compared with results from a Classical Modal Analysis performed on the same machinery. OMA in presence of harmonic components may be difficult to perform. For example, the excitation must have a certain bandwidth and be stochastic in nature. Furthermore, it may be difficult to eliminate the influence of a harmonic component when it is located exactly at the natural frequency of a mode. To improve the analysis methods and understanding of the results from rotating machinery, an OMA - with harmonic components present - has also been performed on a Perspex plate under laboratory conditions. The plate has been analyzed in detail using the CFDD and SSI methods.

1 INTRODUCTION

Modal analysis of large rotating machinery has until a few years ago been limited to Classical Modal Analysis (CMA) on machines, which are at rest. The CMA method has limitations and disadvantages for these types of applications:

- The machine is often very heavy, which makes it more difficult to excite all interesting modes of the machine.
- The dynamical properties of the machine are determined while the machine is at rest. Hence, the influence of e.g. temperature can not be taken into account.

Operational Modal Analysis (OMA) allows the engineer to get a modal model of his machine or structure without shutting it down. There are a number of benefits of using OMA instead of CMA:

- Simplified measurement procedure: the machine can run and needs not be shut down.
- Lower cost for the customer as the machine can run without interruption.
- The modal parameters are determined in their proper operating conditions: for example, the structure's dependence on operating temperature can be investigated.

During operation, the structure is excited by strong harmonic components as a result of the rotating parts and electromagnetic forces of the machine. The response spectra used for OMA will consist of broad banded stochastic noise (The stochastic excitation comes from e.g. the bearings) superimposed by significant harmonic components. This evaluation will examine whether the same modes will be estimated using OMA as was the case for CMA. To improve the analysis of the stator, *a Perspex plate* has been studied to evaluate how different identification techniques can be used in different cases, e.g. for closely-coupled modes and for modes with high damping.

1.1 The harmonic force excitation of a 2-pole rotating machine

The dominant components are one and two times the rotational speed (50 Hz and 100 Hz in a 50 Hz grid). The 50 Hz component originates mainly from rotor unbalance. The major source for the 100 Hz component is the rotating magnetic field, which will excite the stator core and end windings. The operating deflection shape of the stator core and end windings is therefore generally a rotating 4-node motion, as indicated in Fig. 1. Hence, to minimize stator vibration amplitudes, 4-node modes with natural frequencies close to 100 Hz must be avoided.

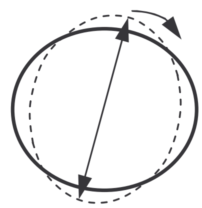


Figure 1 : Rotating 4-node mode shape of an electromagnetic force excitation at 100 Hz.

2 THEORY

Two major classes of identification techniques are used for operational modal analysis: Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification (SSI).

2.1 The Frequency Domain Decomposition techniques

Three sub-classes of techniques of FDD techniques exist: Frequency Domain Decomposition (FDD), Enhanced FDD (EFDD) and Curve-fitted FDD (CFDD). They are all based on simple peak-picking in the Singular Value Decomposition (SVD) plot.

2.2 The FDD technique

The FDD technique has been described in a series of papers, see e.g. Gade et al. (2005). The technique is based on a decomposition of the spectrum of the measured response defined as:

$$G_{yy}(f) = H(f)\, G_{xx}(f)\, H^H(f) \tag{1}$$

where $G_{yy}(f)$, $G_{xx}(f)$ and $H(f)$ are the spectra of the measured response, the unknown excitation and the Frequency Response Function (FRF), respectively. The key step in the FDD technique is to perform a SVD of $G_{yy}(f)$ at the discrete frequencies $f = f_i$:

$$G_{yy}(f_i) = U_i\, S_i\, U_i^H = \sum_{k=1}^{n_y} u_{ki} u_{ki}^H s_{ki}\text{ , } n_y\text{: number of measured responses} \tag{2}$$

If there are no repeated roots, the rank of $G_{yy}(f_n)$ is approx. 1 at the natural frequency $f = f_n$:

$$G_{yy}\left(f_n\right) \sim u_{n1} u_{n1}^H s_{n1} \tag{3}$$

This indicates that at the natural frequency the spectrum is approximately equal to the space spanned by the 1st singular vector multiplied by the 1st singular value. As documented in e.g. Brincker et al. (2000), the vector u_{n1} approximates the mode shape of the mode with natural frequency f_n. As the FDD technique only uses a single frequency component at a time, the natural frequency cannot be estimated with a better accuracy than the resolution of the underlying FFT and calculation of damping estimates cannot be done. The FDD technique is consequently mainly used for fast preliminary analysis.

2.3 The EFDD technique

To obtain damping estimates and to get more accurate estimates of the natural frequencies and mode shapes, the EFDD technique was developed, see Gade et al (2005). The EFDD technique uses the fact, that at the frequencies in the vicinity of a natural frequency the singular vectors have a high MAC value with singular vector at the natural frequency thus enabling to establish a Single-Degree-Of-Freedom (SDOF) spectral density function *S(f)* for the specific mode. This SDOF function is transformed to the time domain yielding an auto-correlation function from where the natural frequency is obtained by determining the number of zero-crossings as function of time using a simple least-square fit.

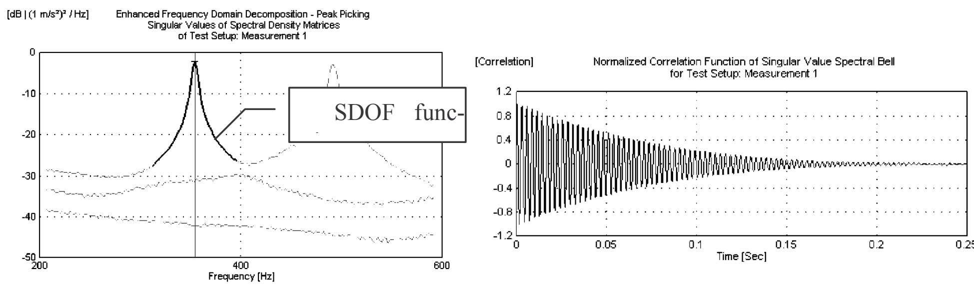


Figure 2 : Identified SDOF function (left) and resulting Auto-correlation function (right).

The damping ratio is obtained from the logarithmic decrement of the auto-correlation function again using a simple least-squares fit. Compared to the FDD technique, an improved estimate of the mode shape is obtained by using a weighted sum of the singular vectors Φ_i and singular values s_i whereby random noise is efficiently averaged out.

$$\Phi_{weight} = \sum_i \Phi_i s_i \tag{4}$$

2.4 The EFDD technique in presence of harmonic components

If a harmonic component is present within the identified SDOF function, the obtained modal parameters can be significantly biased. Consequently, potential harmonic components must be identified and eliminated. The harmonic components are identified using various kurtosis calculations and their effect are removed by using linear interpolation across them, see Jacobsen et al. (2007). However, only the singular vectors at the non-interpolated singular values are used in the estimation of the mode shapes.

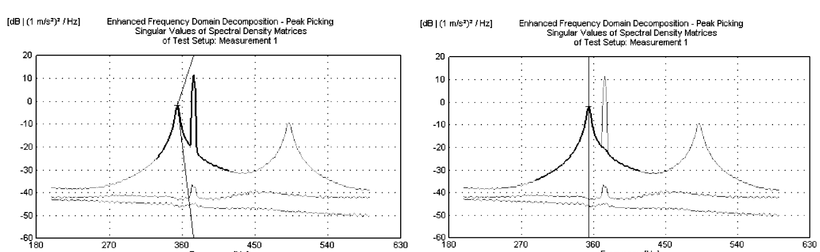


Figure 3 : Identified SDOF function before (left) and after (right) linear interpolation across the harmonic component.

2.5 The CFFD technique

The Curve-fitting Frequency Domain Decomposition (CFDD) technique is an alternative approach to the EFDD technique utilizing curve-fitting directly in the frequency domain to obtain the natural frequencies and damping ratios. The mode shapes are found as in the original EFDD technique. The main advantage of the CFDD technique is a more accurate estimation of the natural frequency and damping ratio, if harmonic components are close to or located exactly at a natural frequency. In Eq. (1) the spectral density was defined in terms of the FRF. The FRF for a SDOF system can be expressed in polynomial form as (see Ljung (1999)):

$$H(f)=\frac{B(f)}{A(f)}=\frac{B_0+B_1e^{2\pi fT}+B_2e^{4\pi fT}}{1+A_1e^{2\pi fT}+A_2e^{4\pi fT}}\text{ , }T\text{: sampling interval} \tag{5}$$

From the roots of *A(f)* the natural frequency and the damping ratio can be extracted.

Assuming the unknown excitation $G_{xx}(f)$ in Eq. (1) can be approximated by broad-banded white noise with constant spectrum $G_{xx}(f) = G_{xx}$, the SDOF spectrum *S(f)* becomes proportional to the product $H(f)H^H(f)$, indicating that the polynomial order of *S*(*f*) is twice the order of *H*(*f*). To fit *H(f)* instead of the product $H(f)H^H(f)$ the full-power spectrum *S*(*f*) is transformed to a positive half-power spectrum.

When harmonic components are present, the curve-fitting is done on the interpolated SDOF function as shown in Fig. 3. Consequently, when using curve-fitting, the linear interpolation is less critical when dealing with harmonic components located exactly at or close to the natural frequency. The CFDD technique is further described in Jacobsen et al. (2008).

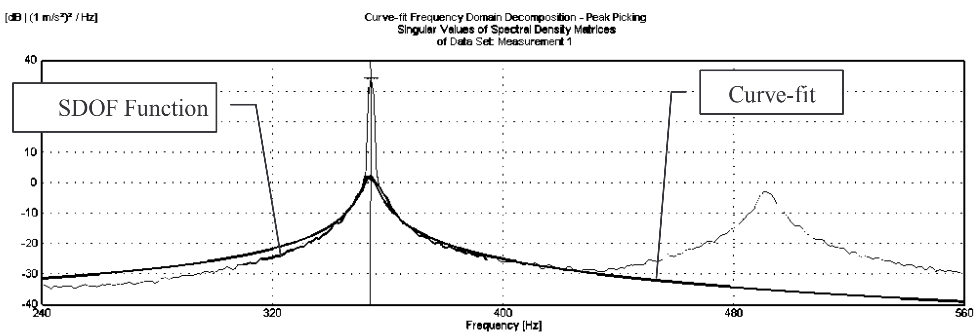


Figure 4 : Curve-fitting (blue curve) of the interpolated SDOF function (red curve). Harmonic component located at the same frequency as the natural frequency of the mode.

2.6 The Stochastic Subspace Identification technique

Stochastic Subspace Identification (SSI) is a parametric technique, where the modal parameters are identified from the matrices of the resulting state-space model derived from raw time domain data. For output-only analysis, as used in operational modal analysis, the state-space model can be formulated as a state equation modeling the dynamics of the system (upper equation in Eq. (6)) and an observation equation modeling the output of the system (lower equation in Eq. (6)).

$$\begin{aligned} x_{t+1} &= Ax_t + w_t \\ y_t &= Cx_t + v_t \end{aligned} \tag{6}$$

where x_t is the state vector, y_t the output vector, w_t the process noise, v_t the measurement noise, *A* the state matrix and *C* the observation (output) matrix. The natural frequencies and damping ratios can indirectly be derived from the state matrix A and the mode shapes from the observation matrix C. More information of SSI can be found in e.g. Møller et al. (2005).

3 MEASUREMENTS

3.1 OMA on large rotating machinery

Response measurements of the stator of a large generator were performed using a 5-channel B&K PULSE™ measurement system. The data was analyzed to determine the vibration behaviour during full load operation. The results from the OMA have been compared to CMA measurements made on the same stator. A principal sketch of a generator is shown in Fig. 5, and the OMA geometry is shown in Fig. 6, where radial and axial measurement point directions are marked by arrows. In the analysis, three (3) reference channels were used. The frequency resolution was 0.4 Hz.

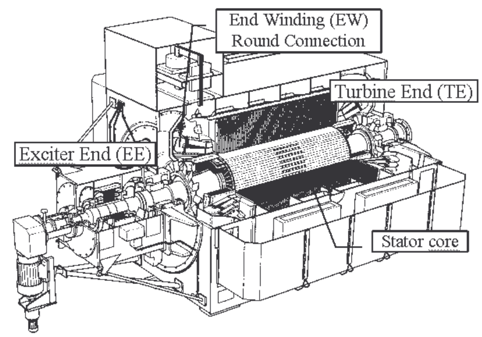


Figure 5 : Principal sketch of 2-pole generator.

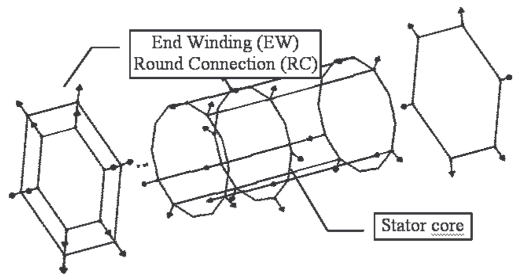


Figure 6 : OMA geometry.

4 RESULTS

In Table 1, the results from the OMA of the stator are compared with the CMA of the same stator. Some mode shapes are presented in Figs. 7, 8.

Table 1: Results from operational modal analysis compared with classical modal analysis.

Mode	CMA / OMA (Orthogonal Polynomial* / EFDD, CFDD, SSI) Mode Shape: End Winding (Turbine End)	Stator Core	End Winding (Exciter End) & Round Connection	CMA Freq. [Hz]	OMA Freq. [Hz]
1	Tilting		Tilting EW & RC	38	38
2	Tilting		Tilting EW & RC	43	42-43
3	Tilting		Tilting EW	54-56	53-55
4	Tilting		Tilting EW	60	60-61
5		Radial Tilting		65 ; 68	64
6	4-node		4 Node EW	74-75 ; 77	71-72 ; 73
7		Axial Tilting		83	82-83
8			4 Node RC	89	86
9		Lat. & Vert. Bend.		104 ; 106	106
10**			X*** / 6 Node EW	X***	117
11			6 Node RC	118	117
12**			6 Node EW / 6 Node RC	132	130-131
13	6 -node			136 ; 140	130-132
14	Breathing****			151	141; 156

* ME'Scope Version 5.0.
** The mode shapes showed differences between CMA and OMA.
*** Not found
**** First order radial mode shape.

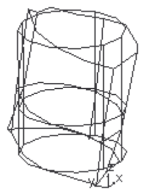


Figure 7 : Mode 7, axial tilting mode of stator.

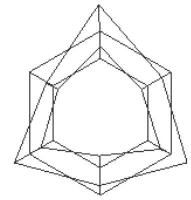


Figure 8 : Mode 11, 6-node mode of the Round Connection (Exciter End).

5 CONCLUSIONS

5.1 Conclusion from stator measurements

The stator data was challenging to analyse. This is probably not due to the prominent harmonic components, but due to the fact that the modes are either not well-excited or that their loss factors are quite high. Therefore, the analysis was concentrated in finding the same modes as were found by the CMA. Both FDD methods and SSI methods were used.

The FDD methods were used to get a first estimation of the natural frequency and loss factor of each mode. The SSI methods were quite cumbersome to use due to the rather complicated stabilization diagrams. The estimation from the FDD methods however helped to make the SSI analysis feasible. Furthermore, both high-pass and low-pass filtering was used to improve the analysis with SSI. In Fig. 9, a high pass filter with cut-off frequency of 90 Hz improves the analysis of higher modes: the synthesized auto spectrum shows a better relation to the measured. However, the previous knowledge about the structure's dynamic behaviour from the CMA facilitated a successful OMA.

For the stator, the natural frequencies determined by the OMA analysis are generally lower than for the EMA analysis. This phenomenon may be due to increased temperature of the stator during operation, thus making the structure softer.

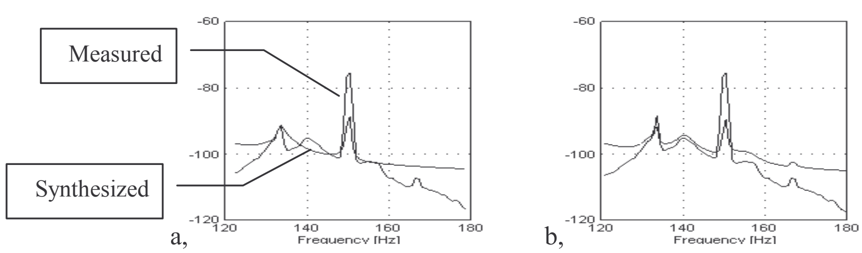


Figure 9: Measured autospectrum (green) compared to synthesized (red) for **a,** non-filtered and **b,** high pass filtered data.

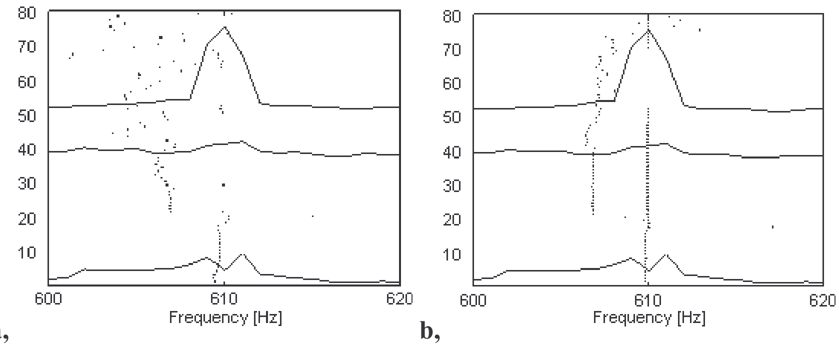
The measurements could be improved to optimize the analysis:

- The consistency of the measured data could be improved if the measurements were performed with a system capable of recording more than five channels, resulting in fewer data sets. As the excitation forces of the generator probably are time-variant, they will slightly change between the data sets. Less data sets will therefore improve the analysis.
- More measurement points could be used for easier interpretation of the mode shapes.
- Longer time recording lengths to allow decimation while maintaining a high BT product to reduce the ripple in the SVD spectra. Especially important for extracting low order modes.

5.2 Conclusion from measurements on Perspex plate

The FDD methods (EFDD and CFDD) and SSI methods could successfully estimate the modal parameters even if a harmonic component was placed in the vicinity of the mode. For some amplitudes of the harmonic, though, the harmonic detection did not properly indicate it. The harmonic was however clearly visual, thus making indication by hand possible.

When dealing with harmonics, a high max state space dimension (the maximum dimension of the matrices in the state space model of SSI) resulted in stabilization diagrams stabilizing faster as shown in Fig. 10. This will make the diagrams easier to interpret and the modal parameters to be more accurately estimated.



a, b,

Figure 10: Stabilization diagrams computed with a max state dimension of a, 80 and b, 200 (zoomed in on dimension 0-80). Mode at 607 Hz and harmonic component at 610 Hz.

If all channels are used instead of a limited number of projection channels (channels, which are considered by calculation to include most information about the dynamics of the system and thus decreasing the computation time), the estimation of the modal parameters may be improved, when analyzing data with the FDD methods. This is especially significant when harmonics are present.

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