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Method of shifted order spectra – identification of spatial orders of electric machines

J. Otta[a], P. Macák[b]

[a] ZF Friedrichshafen AG, 88038 Friedrichshafen, Germany
[b] ZF Engineering Plzeň s.r.o., Macháčkova 24, 318 00 Plzeň, Czech Republic

1. Introduction

Hybrid and electric cars are becoming increasingly quiet, therefore the aspects of Noise, Vibration and Harshness (NVH) gained a very important role in the development of electric drives. One of the main excitation sources of the electric motors is the rotating magnetic field exciting radial eigenmodes of stator.

Typical processing of NVH measurement data can detect relevant time orders of the electric motor, see Fig. 1a, but is not able to identify the shape of the force-waves (spatial orders) acting in the air gap between stator and rotor. This paper presents a method for processing measured NVH data based on averaging of phase-shifted spectra of sensors located around stator to determine spatial orders of excitation forces.

2. Permanent magnet synchronous electric motor excitation

A typical permanent magnet synchronous electric motor (PMSM) contains stator and rotor. Stator consists of outer yoke, and teeth with windings. Alternating currents flowing in winding induce rotating magnetic field in stator. The magnetic field in the rotor is generated by permanent magnets, which follows the rotating field of stator [5] due to magnetic and reluctance torque.

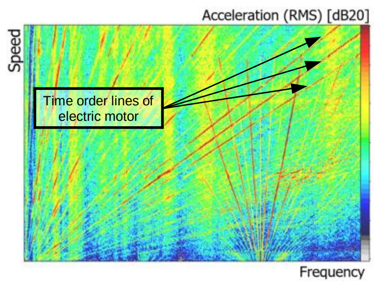


Fig. 1a. Typical Campbell diagramm of NVH measurement with highlighted time orders, [3]

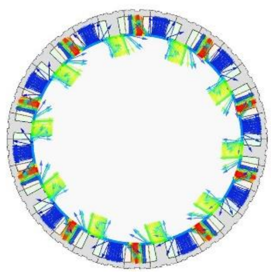


Fig. 1b. Example of forces acting on the stator of a PMSM

Harmonic forces that act in the air gap between stator and rotor, see example in Fig. 1b, can be decomposed as a sum of cosine waves [4]

$$f(\varphi,t) = f_0 + \sum_{s,n} f_{s,n} cos\left(s\varphi - n\omega t - \alpha_{s,n}\right), \quad (1)$$

where ω is angular velocity, s is space order (SO), n is time order (TO), φ is angular coordinate, $\alpha_{s,n}$ corresponds to phase offset and $f_{s,n}$ corresponds to the amplitude of the force-wave for time order n and spatial order s.

Wave direciton and count of waves around circumference define the number of spatial order *s*, see examples in Fig. 2. The time order *n* is a dimensionless quantity that expresses the ratio between excitation frequency and reference frequency, in this case rotor revolutions per second. Time order can be understood as a multiple of the spatial order *s* and the ratio of angular velocity of rotating SO wave to the angular velocity of rotor, cf. Fig. 2.

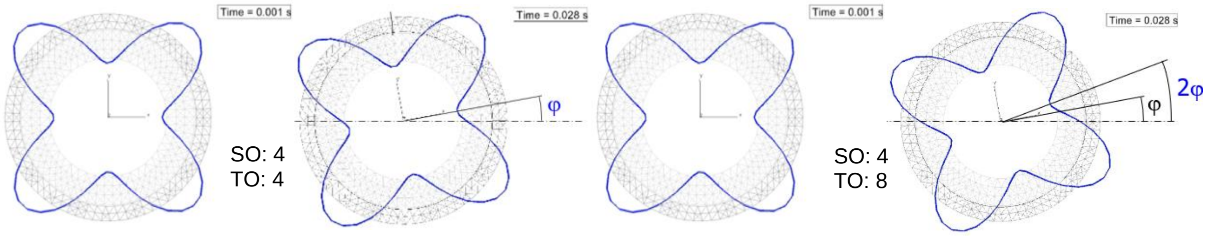


Fig. 2. Example of force waves for SO = 4 and TO = 4, 8

3. Method principle

NVH measurement, in which only one sensor is used in the vicinity of the stator, can detect TO but does not allow any distinction between different spatial orders. On the other hand, if multiple sensors are used, the evaluation of spatial orders could help to understand the system behaviour but does not allow the contributions of each SO to be quantified and identified, see Fig. 3. This is only possible if phases of the signals are processed each one by one.

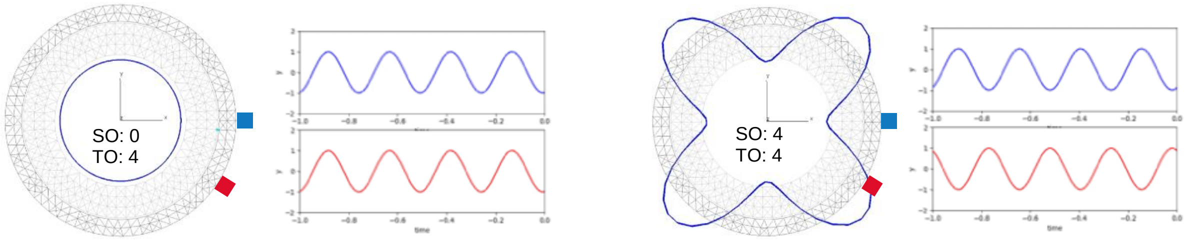


Fig. 3. Importance of the phase information for SO and TO detection. Deflection shape can be identified using phase information from more accelerometers only

3.1 Sensor placement, measurement

The sensors should be placed (ideally equidistantly) around the stator circumference in one plane perpendicular to the rotor, see Fig. 4. It is recommended to use 3D accelerometers or a set of 1D accelerometers measuring radial direction. The sensors can also be placed on a housing (or stator carrier) but only if the stator is connected to these parts by press-fit and not by discrete connections as bolts.

The NVH measurement is performed for a run-up with constant torque. The frequency domain accelerometer data are processed in the form of complex order cuts with given order bandwidth.

(a)

(b)

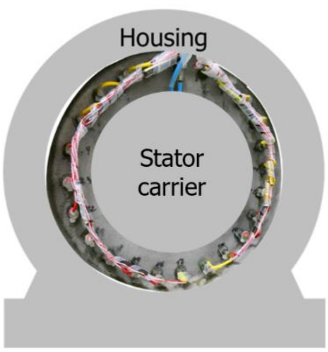


Fig. 4. Illustration of sensors placement on stator (a), stator carrier (b)

3.2 Data processing

The basic idea of the method can be illustrated on the example of stator deflection in time domain under harmonic excitation by spatial orders s = 1, 2 and 3, see Fig. 5.

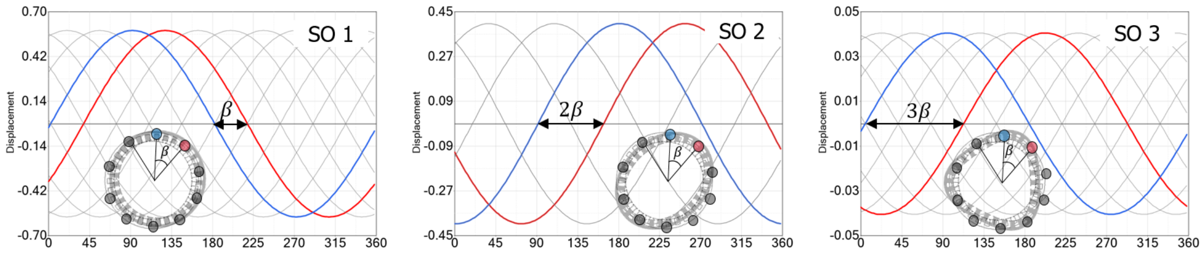


Fig. 5. Phase-shift of signals between 2 sensors in the time domain is product of spatial angle β between the sensors and SO number s = 0, 1, 2

Deformations are evaluated at equidistant positions in the time domain. The phase shift of the system response can be observed in dependence on the number of spatial order s and sensor angular coordinate β.

To evaluate the spatial order number s, the original sensor data are proportionally modified as follows [2]:

- The phase of the sensor signals is shifted by

$$\varphi = \varphi_0 + \beta s\,, \qquad \text{for } s = 0,\ \pm 1, \dots, \frac{N}{2} - 1\,, \tag{2}$$

  where φ_0 is original measured phase angle, β stands for the spatial angle between the sensor and reference sensor (see Fig. 5), N is total count of the sensors, s is the number of the spatial order to be evaluated.

- Shifted order spectra $A_s(f)$ for each sensor position j w.r.t spatial order s are then arithmetically averaged (complex sum divided by number of sensors N) as

$$A_s(f) = \frac{1}{N}\sum_{j=1}^{N} a_j(f) e^{i\beta s}\,. \tag{3}$$

Maximal spatial order to be evaluated is limited by Nyquist-Shannon sampling theorem, [3]. Shifted average spectra (3) allows to identify, which spatial order is dominating in given frequency. Arithmetic sum of complex signals from all sensors are amplified, if their phases are same (or similar) and supressed if the phases differ, see Fig. 5. Therefore the dominance of shifted order spectrum $A_s(f)$ for some s among other spatial orders indicates that the highest contribution to the stator reponse comes from spatial order s.

4. Method testing and application

The method is illustrated on example of the FE model of single stator, see Fig. 6. The stator is excited by superimposed unit-force excitation by spatial order s = 0, 2, 3, 5. The system response in all 10 positions is presented in Fig. 6a. Data processed by (3) in Fig. 6b show that the peaks in the RMS data from all 10 sensors are dominated by spatial orders exactly at the eigenfrequencies corresponding to the radial eigenmodes of (oval shape, triangular shape, breathing shape).

Example of the method applied on the measurement data illustrates Fig. 7. Evaluation has been performed on an electric machine (PMSM, 3 phase, 30 slots, 10 pole pairs) with 24 uniaxial sensors located on the stator carrier, see Fig. 4b. The method of shifted order spectra has been applied to the fundamental time order of electric machine, i.e. n = 60.

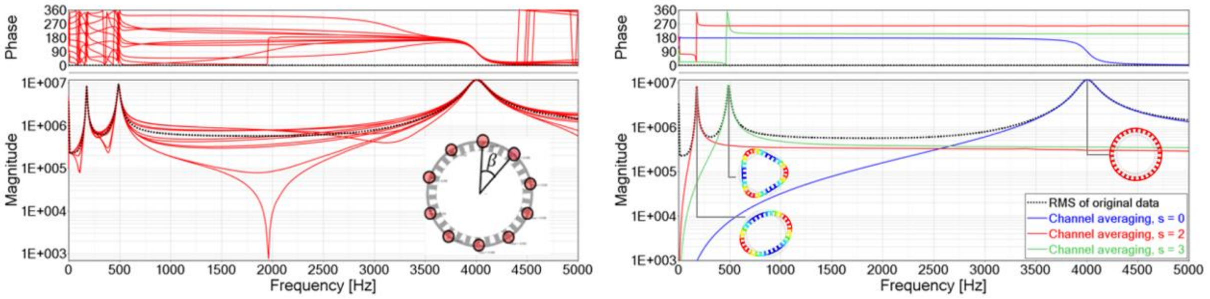
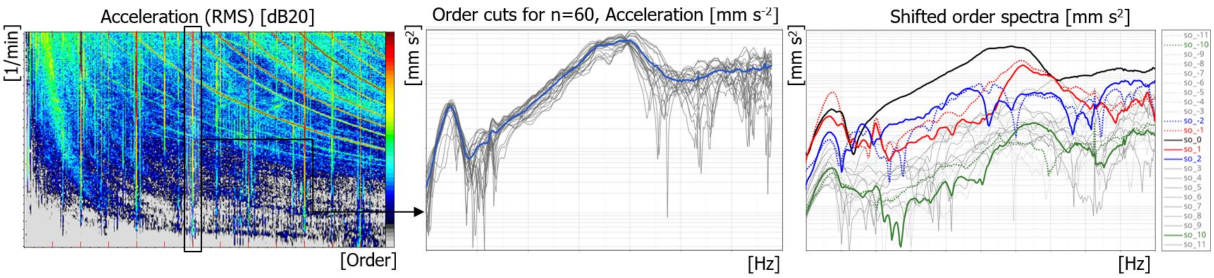


Fig. 6. (a) Original data, (b) results of shifted channel averaging

In a healthy machine, the root cause of vibrations for time order $n = 60$ is usually expected as a pulsating excitation by spatial order $s = 0$. Observed high contributions of spatial order $s = \pm 1$ can be explained by non-uniform magnetic pull caused by uneven magnetization or static eccentricity [3].



(a) (b) (c)

Fig. 7. Evaluation of shifted order spectra for electric motor with fault. (a) Campbell diagram with acceleration results for 1 given sensor, (b) order cuts for $n = 60$ for all sensors with their RMS curve, (c) evaluation of shifted order spectra for s, $-11 \leq s \leq 11$

5. Limitations

Method of shifted order spectra enables to identify the root cause of stator resonances in electric motors. The method has practical limitations in cases where stiffness of the measured area is not uniform or when there is no possibility to measure directly in one plane. In such cases a hybrid approach can be used that combines simulated transfer functions from stator teeth to the accelerometer positions with measured responses in the accelerometers.

Acknowledgements

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