Pseudo random binary signal for MIMO frequency response identification of a magnetically levitated rotor system

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Abstract. High-speed machine technology with magnetically levitated rotor systems has become interesting solution in modern compressor, pump and turbo applications. Often, the commissioning of such machines is system identification-based with injected artificially generated excitation. In this paper a statistically uncorrelated PRBS design is proposed for multi-input multi-output MIMO system that gives the possibility to utilize same PRBS signal for all inputs. The proposed routine is validated with an experimental high-speed generator with active magnetic bearings (AMBs). The obtained frequency responses are validated by comparing the results with the mathematical model.

1. Introduction
System identification based commissioning with artificially generated excitation signals is in a key role in modern high-speed machines with magnetically levitated rotor systems. To obtain high-performance model-based control the identification data is needed to update the model of the rotor system. In general, the literature covering the identification of multiple input multiple output (MIMO) dynamics of such machines the applied excitation signals are based on multi-sine [1], stepped sine [2], chirp [3], [4], [5] or pseudo-random binary signal (PRBS) [6] designs. Typically the identification experiments are simplified and carried out in a single input multiple output (SIMO) or SISO manner. This is often justified, as the model used for control design can be updated based on such experiments. Some studies considers MIMO experiments in AMB systems, but the identification has been carried out in a two degree of freedom (2-DOF) manner [7], [8].

It is well known that, AMB supported rotor system is unstable and nonlinear in nature, hence the identification must be carried out in a closed loop and the nonlinearities has an effect to the obtained results. However, when the identification experiments is carried out in a narrow and almost linear position region, the excitation signal type can be freely selected. In [9] it is shown that different excitation signals produce similar identification results, when applied for commissioning purpose of AMB supported rotor system. This paper addressed issues in MIMO identification experiments of a high-speed machine by considering PRBS excitation signal that is designed to be statistically uncorrelated for MIMO identification experiments. This gives the possibility to inject the same excitation signal design for all the inputs simultaneously. The proposed routine is validated with a high speed machine, namely a 1 MW and 12 500 rpm hermetic steam turbo generator.

2. Identification of flexible rotor system
In Figure 1 the generalized structure of the MIMO closed loop identification is depicted where multiple PRBS excitation signal injection is considered. The PRBS excitation are superposed to the position
control output and signals used for the identification are the excitation and the measured input (current references) and output (positions) signals.

Figure 1. The MIMO closed loop identification experiment.

2.1. Closed-Loop Identification Experiments

The general expression for the direct frequency response estimation from the input and output signals can be expressed by the ratio of spectral density functions as follows

\[ G(j\omega) = \frac{S_{uy}(j\omega)}{S_{uu}(j\omega)} \],

where \( S_{uy}(j\omega) \) is the cross spectral estimate between input \( u(t) \) and output \( y(t) \) signals and \( S_{uu}(j\omega) \) is the auto spectral estimate of the input signal. In the case of MIMO systems, the frequency response estimation of \( p \) input and \( q \) output system can be expressed in a similar form

\[ G^{H}(j\omega)_{(p \times q)} = S_{uu}^{-1}(j\omega)_{(p \times q)} \cdot S_{yy}(j\omega)_{(p \times q)}, \]

where \( G^{H}(j\omega) \) is the Hermitian of the frequency response matrix. The radial controller is a \( H_{\infty} \) type that is tuned based on mixed sensitivity synthesis method. The controller \( K \) is found by minimizing

\[ \| W_s S \|_\infty \leq 1, \]

where \( S \) is the sensitivity function and \( W_s \) is its design weight whereas the \( W_u \) is the design weight for the control effort. The sensitivity weight is selected as

\[ W_s(s) = \frac{s A}{s + \omega_B} \]

where the parameter \( A \) indicates the steady state error and initially selected as 0.001. The \( \omega_B \) is the crossover frequency that is here selected as 67.5 rad/s. The \( M_s = 2 \) is selected that indicates the desired maximum peak of the sensitivity functions. The control effort is limited by following first order weight

\[ W_u(s) = \frac{s + \omega_{BC}}{A_u s + \omega_{BC}} \]

where \( \omega_{BC} \) is the controller bandwidth and \( M_u \) maximum gain of \( K(s)S(s) \). Values of \( \omega_{BC} = 10000, M_u = 50 \) and \( A_u = 4 \) has been selected for the radial controller control effort design.

2.2. PRBS Design

To design a PRBS signal several good guidelines can be found, like [10]. In the case of MIMO system, the same PRBS can be used if it is time shifted [11] to make them statistically uncorrelated by

\[ r_{u,m}(t) = A_m u_{PRBS}(t - \theta_m), \quad m = 1, 2, \ldots, p \]
where $A_m$ is the amplitude of the signal, and the time shift can be selected as $\theta_m = N \cdot T_{sw} \cdot (m-1)/p$, where $N$ is the length of the signal with the switching time $T_{sw}$. The length of the signal is determined by the amount of shift registers $d$ as

$$N = 2^d - 1$$  \hspace{1cm} (7)

An example of a statistically uncorrelated 6-cell PRBS with a switching time of $T_{sw} = 6 \cdot T_s$ (when $T_s = 0.0067s$) design for a system with four inputs is shown in Fig. 2 a), where the time shift of 0.63 seconds is shown with red arrows. The effective band of the PRBS show in Fig. 2 b) can be expressed as

$$f_{BW} = \frac{1}{3 T_{sw}},$$  \hspace{1cm} (8)

representing the -3 dB drop in the signal. Hence, the frequencies to be covered with the effective band is important to consider in the PRBS design. A practical selection for the PRBS switching time is $[12]$

$$T_{sw} \approx \frac{2.5}{\omega_{max}},$$  \hspace{1cm} (9)

where $\omega_{max}$ can be often taken as a desired bandwidth of the closed loop system. In an AMB supported rotor system the signal should in general cover the frequencies of the rigid modes, and depending on the case, at least the first flexible mode. In Fig. 2 c) the PRBS generator is shown, that is, a maximum length binary signal generator with XOR feedback. Depending on the desired length of the shift register, the optimal maximum length signal is obtained by following the guidelines given in $[13]$.

3. Hermetic steam turbo generator

The high speed turbo generator consist of two main components; the turbine part and the electric machine. The generator is an induction generator with nominal power of 1 MW and 12 500 rpm that is controlled with ACSM1 frequency converters. The control and the excitation signals are implemented by Beckhoff’s TwinCAT. The experimental system is shown in Fig. 3 a)–c). The radial and axial bearings are shown in Fig. 3 b) and the main parameters in Table 1.

| Table 1. The parameters of axial and radial AMBs. |
|-----------------------------------------------|
| Value                                        | Axial AMB | Radial AMB 1 | Radial AMB 2 |
| Current Stiffness [N/A]                      | 581       | 170          | 270          |
| Position Stiffness [N/µm]                    | 5.68      | 1.19         | 1.88         |
| Max. Force [N]                               | 1110      | 1760         | 6360         |
| Number of poles                              | 2         | 12           | 12           |
| Number of winding turns                      | 65        | 54           | 85           |
| Material                                     | X20Cr13   | SURAM270-35A0| SURAM270-35A |
4. Experimental results
The MIMO identification routine under study is considered during full levitation but without rotation. This stage correspond to initial commissioning step needed for identification for control [14]. The data acquisition and control is operated in a sample level of $T_s = 100 \, \mu$s. The 6 times repeated PRBSs are generated with a 15-cell generator operating at $6 \cdot T_s$ with amplitude of 0.5 A. The initial mathematical model based on the mechanical design is used for comparison of the experimental results.

The experimentally obtained frequency responses (Nx-Nx, Ny-Ny, Dx-Dx, Dy-Dy) are shown in Fig. 4 and compared to the mathematical model of the rotor dynamics. It can be observed that the MIMO PRBS identification experiment provide reasonable results when compared to the modeled ones. The resonances can be clearly seen and the dynamics correspond well to each other. In Fig. 5, the MIMO frequency responses are shown for all input-output pairs of the measurement. The first resonance is clearly visible on all of the responses as well as the cross-coupling dynamics. On the same coordinate axis response but on the different end (e.g Dx-Nx) the responses are more accurate and the second resonance and first/second anti-resonances are also visible in some cases.
5. Conclusions

This paper studied the commissioning of an AMB supported high-speed generator by applying MIMO identification experiments. A statistically uncorrelated PRBS design was considered as an excitation signal that was injected to the controlled inputs simultaneously. Based on the obtained frequency responses, the proposed PRBS-based identification routine provides straightforward approach for the commissioning of a MIMO system. More importantly, the PRBS gives several advantages for MIMO system identification of AMB dynamics; it is relatively easy to design, implement and generate.

References

[1] Hynynen K 2011 Broadband excitation in the system identification of active magnetic bearing rotor systems,” Ph.D. dissertation, LUT University
[2] Smirnov A 2012 Amb system for high-speed motors using automatic commissioning,” Ph.D. dissertation, LUT University
[3] Lanzon A and Tsiotras P 2005 A combined application of H∞ loop shaping and μ-synthesis to control highspeed flywheels IEEE Trans. on Control Systems Techn. 13(5) 766–77
[4] Kasarda M, Quinn D, Bash T, Mani G, Inman D J, Kirk R and Sawicki J T 2005 Magnetic bearings for non-destructive health monitoring of rotating machinery supported in conventional bearings *Damage Assessment of Structures VI*, ser. Key Engineering Materials 293 383-90.

[5] Noshadi A, Shi J, Lee W S, Shi P and Kalam A 2016 System identification and robust control of multiinput multi-output active magnetic bearing systems *IEEE Trans. on Control Systems Techn* 24(4) 1227–39

[6] Vuojolainen J, Nevaranta N, Jastrzebski R and Pyrhönen O Using a pseudorandom binary sequence for rotor-bearing system identification in active magnetic bearing systems, In Proc. of 15th Int. Symp. on Mag. Bear. (ISMB) 618–25 20176.

[7] Hynynen K, Jastrzebski R P and Smirnov A 2010 Experimental analysis of frequency response function estimation methods for active magnetic bearing rotor system in Proc. of 12th Int. Symp. on Mag. Bear. (ISMB), 40–46.

[8] Hynynen K and Jastrzebski R P 2009 Optimized excitation signals in amb rotor system identification in *LASTED Int. Conf. of Ident, Contr. and Appl.* 1–6.

[9] Vuojolainen J, Nevaranta N, Jastrzebski R, Pyrhönen O. 2017 Comparison of excitation signals in active magnetic bearing system identification *Modeling, Ident. and Control* 38(3) 123-33

[10] Vilkko T Matti, Roinila 2008 Designing maximum length sequence signal for frequency response measurement of switched mode converters, *Proc. of the Nordic Workshop on Power and Ind. Electron. (NORPIE/2008)* 1–6

[11] Häggblo K E 2016 Evaluation of experiment designs for mimo identification by cross-validation *IFACPapersOnLine* 49(7) 308–13.

[12] Pintelon R and Schoukens J 2010 System Identification: A Frequency Domain Approach. Wiley

[13] Pacas M, Villwock S, Szczupak P and Zoubek H 2010 Methods for commissioning and identification in drives *COMPEL - The int. jour. for comp. and math. in electrical and electron. eng.* 29(1) 53–71

[14] Jaatinen P, Vuojolainen J, Nevaranta N, Jastrzebski R Pyrhönen O. 2019 Control System Commissioning of Fully Levitated Bearingless Machine *Mod, Ident. and Control* 40(1) 27–39.