Real-Time Multiple Resonance Peak Detection in Servo Drive Applications

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Abstract—**The performance of gearless servo drives is significantly degraded by mechanical resonances in the system. For applications the parameters of the mechanical resonances of a drive are not known a priori. In order to improve the identification process of resonance frequencies this article introduces a simple and efficient real-time capable algorithm to detect multiple resonance frequencies in a single identification run. The algorithm will be implemented using a digital signal processor which runs on a frequency inverter. It uses the frequency neighborhood to compute peaks. The performance of the algorithm is shown with a synthetic multisine signal and a measurement on a machine, where a workpiece is mounted on a direct torque round table.**

Index Terms—**resonance peak detection; servo motors; notch filter; adaptive; online; system identification; simultaneous detection; real time**

I. Introduction

Servo motors are commonly used in industrial fields such as robotics or machines. An industrial system using a servo motor usually includes several other parts, for example a frequency inverter, a gear, an encoder and a mechanical plant.

Regarding machines, workpieces can be mounted on a round table. They typically cannot be treated as an end-lessly stiff connection due to high gains in the controller. Thus, the mechanical plant includes an elastic coupled load which will lead to resonances in the machine and thus degrade the performance, because it can lead to high position tracking errors.

Unknown resonances require a robust control design. The most common way is to reduce the controller gains which will lead to poor tracking performance.

The traditional servo motor system includes a gear. When direct drives are used no gear is present in the system. This leads to an increased impact of mechanical resonances in the control system, thus increasing the demand to dampen those resonances. In machines different workpieces shall be processed which results in different plant settings (masses, stiffnesses and dampings). The plant characteristic is typically a two- or three-mass system.

A common control optimization attempt is the direct identification of mechanical resonances without generating a parameterized plant model. If the mechanical resonance parameters can be identified (mainly resonance frequency and damping), a notch filter can be used to dampen the resonance. This has been shown in [1]. The main benefit of this approach is that no a priori knowledge of the plant is required.

[2] has already discussed different frequency identification algorithms ([3], [4], [5]). [6] gives a good overview of different methods to dampen vibrations with adaptive regulations. [2] has proposed a modified Scanning-Algorithm based on [7] which uses a band-pass filter to identify the frequency response of a signal. This method will be used in this paper to detect multiple resonance peaks in the spectrum.

The identification of peaks has gained a lot of interest for the detection of harmonic and inter-harmonic signals in power systems. [8] gives a good overview on different methods to estimate stationary and time varying signals for harmonics and interharmonics. In [9], an improved FFT algorithm was used to identify power system harmonics and interharmonics.

Notch filters are effective to dampen resonances that occur in servo machines. This is especially important when the plant characteristics change significantly due to different workpieces mounted on round tables. To increase the overall machine performance all significant resonances have to be identified and damped to be able to increase the controller gain. This paper transfers the aspect of detecting multiple peaks to design notch filters for servo machines in one identification process and thus decreases the identification time.

Section II gives an overview of the used system. Section II-B introduces some key aspects of resonance peaks modeling. Section III introduces the proposed algorithm capable to detect multiple resonance peaks in one identification run. The prove of concept is done with a synthetic signal in Section IV and afterwards transferred on an industrial machine in Section V. These tests are performed on a gearless direct torque drive in the presence of multiple resonances, which will be detected with the proposed algorithm.

Manuscript received March 21, 2018; revised August 2, 2018.

doi: 10.18178/ijmerr.7.5.569-574

II. System Model

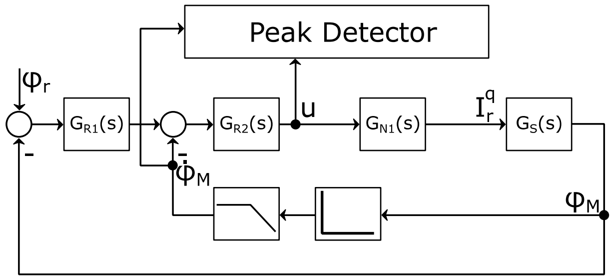

Figure 1. Block Diagram of the Control System. The plant includes the current control loop and the mechanical plant.

The control system consists of three cascaded PI controllers for current, speed and position. The position and speed feedback will be generated from an encoder attached to the torque drive. Therefore the mechanical resonances will mainly affect the position and derived speed feedback.

Fig. 1 shows a simplified block diagram of the used control system. The position reference φ_r will be generated by a software shipped with the machine. The measured position φ_M ('M' referring to the motor position) describes the actual position of the round table seen on the motor side, which will be fed into the position PI controller $G_{R1}(s)$. The variable $\dot{\varphi}_M$ describes the measured speed, u is the output of the speed PI controller $G_{R2}(s)$ and I_r^q describes the current reference. The superscript 'q' is typically used in field-oriented current control topology, which is used in this paper, and denotes the current perpendicular to the electric motor field. This current is approximately proportional to the resulting motor torque, if parasitic electrical effects such as cogging and reluctance are neglected. The mechanical resonances can be dampened in the current reference signal statically with the block called $G_{N1}(s)$ as shown in Equation 1:

$$G_{N1}(s) = \frac{s^2 + g\Delta\omega\omega_{Res}s + \omega_{Res}^2}{s^2 + \Delta\omega\omega_{Res}s + \omega_{Res}^2} \tag{1}$$

A. Modelling the Control Plant

For the sake of simplicity the plant $G_S(s)$ includes the current controller, the electrical plant (from current to a mechanical torque in the motor) and the mechanical plant (motor torque to position). All parts of the plant shall be treated as linear systems, the electrical shall also be time invariant. It follows:

$$G_S(s) = G_{el}(s) \cdot G_M(s) \tag{2}$$

The transfer function $G_M(s)$ describes the mechanical part of the plant which will be explained in the next section. The electrical part of the plant uses the current reference I_r^q to generate a motor torque M_M and can be described as:

$$G_M(s) = \frac{M_M(s)}{I_r^q(s)} = \frac{k_f}{T_e s + 1} \tag{3}$$

The parameter k_f is a motor constant and can be derived from the motor datasheet, T_e is the equivalent time constant of the current cascade loop, which is typically $T_e \approx 2T_t$ with T_t being the power converter time constant. For in depth analysis of modeling the used electrical machine refer to [10].

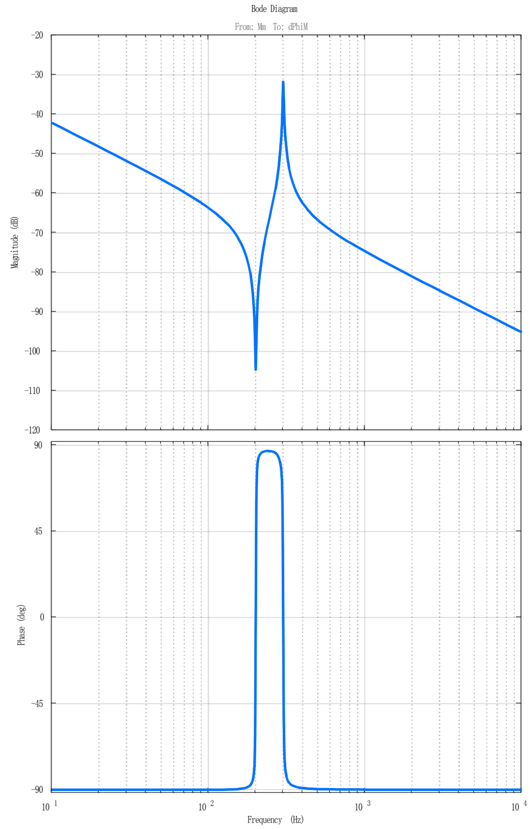

Figure 2 Bode diagram of simulated two-mass system with respect to the motor side. For parameters see Table I.

The mechanical part of the plant mainly consists of an double-integrating-system with an elastic load. The integral of the motor torque $M_M(s)$ leads to the speed $\dot{\varphi}$ and position φ.

Based on [10] the plant can be described with respect to the load side position φ_A or the motor side position φ_M. The first approach is to model the mechanical plant as an elastic load, thus being a two-mass system. The description of a two-mass system was developed in [10] and states the following:

$$G_A(s) = \frac{\dot{\varphi}_A(s)}{M_M(s)} = G_{Rigid}(s) \cdot G_{ElastA}(s) \tag{4}$$

$$G_M(s) = \frac{\dot{\varphi}_M(s)}{M_M(s)} = G_{Rigid}(s) \cdot G_{ElastM}(s) \tag{5}$$

$$G_{Rigid}(s) = \frac{1}{s(\Theta_M + \Theta_A)} \tag{6}$$

$$G_{ElastA}(s) = \frac{1 + \frac{d}{c}s}{1 + \frac{d}{c}s + \frac{\Theta_M\Theta_A}{c(\Theta_M + \Theta_A)}s^2} \tag{7}$$

$$G_{ElastM}(s) = \frac{1 + \frac{d}{c}s + \frac{\Theta_A}{c}s^2}{1 + \frac{d}{c}s + \frac{\Theta_M \Theta_A}{c(\Theta_M + \Theta_A)}s^2} \quad (8)$$

The transfer function $G_A(s)$ describes the characteristic between motor torque M_M and load side speed $\dot{\varphi}_A$, whereas the transfer function $G_M(s)$ denotes the motor side speed $\dot{\varphi}_M$ with respect to the motor side moment M_M. The mechanical system can be split into a rigid coupled component $G_{Rigid}(s)$ and in the elastic coupled component $G_{ElastA}(s)$ or $G_{ElastM}(s)$. The component $G_{Rigid}(s)$ is relevant for frequencies significantly below the respective resonance frequency ω_0, which will be derived in the next section. The overall inertia is reduced by the elastic component for frequencies $\omega \gg \omega_0$. This can be observed in the typical bode plot of an two mass system in Fig. 2. The system parameters d and c will be derived in the next section, the motor inertia Θ_M can be obtained from the motor datasheet whereas the load inertia Θ_A significantly depends on the mounted workpiece. This was derived in detail by [11].

Dependent on the specific application it can be of interest to control the load side position φ_A or motor side position φ_M. The position is typically measured at the motor side via an encoder, so the load side position can be modeled via an observer. Nevertheless, the impact of the load side inertia and resonance can be observed at the motor side and therefore a notch filter can be used at the occurring resonance frequency. This will dampen the load side resonance without the need to observe the load side position.

TABLE I PARAMETERS USED FOR SIMULATION OF A TWO-MASS SYSTEM SHOWN IN FIG. 2

Parameter	Value
ω_0	$2\pi 300 \frac{rad}{sec}$
Θ_A	$1.24 \frac{kgm}{sec}$
Θ_M	$1 \frac{kgm}{sec}$
d	$6.2\ 10^{-3}$

B. Modeling Peaks in Control Plants

Assuming the control plant is modelled as a multi-mass system, multiple resonance peaks are present in the system. In a typical machine additional mechanical resonances exist and can be observed.

The common way to represent a resonant system $G(s)$ with resonance frequency ω_0 and damping D can be described as:

$$G(s) = \frac{1}{1 + \frac{2D}{\omega_0}s + \frac{1}{\omega_0^2}s^2} \quad (9)$$

The quality factor Q can be used to describe the bandwidth B of the resonance peak seen in the transfer function of $G(s)$:

$$Q = \frac{1}{2D} \quad (10)$$

$$B = \frac{\omega_0}{Q} = 2D\omega_0 \quad (11)$$

The damping D and resonance frequency ω_0 can directly be measured in a physical system. An alternative representation utilizes datasheet parameters from a spring-mass systems with spring constant c_{12}, damper constant d_{12} and load inertia Θ_M. Using these parameters the following equations can be used which lead to $G(s)$:

$$\omega_0 = \sqrt{\frac{c_{12}}{\Theta_A}} \quad (12)$$

$$D = \frac{d_{12}\omega_0}{2c_{12}} \quad (13)$$

Mechanical resonances besides the multi-mass resonances are typically weakly damped and are visible as a sharp peak in a bode diagram of a system or spectrum of a signal. Thus, it is viable to use a small frequency step size, e.g. 5 Hz.

C. Defining a Frequency Neighborhood

Since the plant contains an open integrator, mechanical resonances occurring at high frequencies are naturally damped. Nevertheless they can deteriorate the controller performance and have to be detected as well as mechanical resonance frequencies occurring at lower frequencies (e.g. $f_{Res} < 1000\ Hz$).

It is therefore necessary to define a frequency neighborhood and measure peaks relative to it. The neighborhood shall be defined as a frequency band Δf_{NB} close to each measured power sample. This can be achieved by calculating a moving average of this frequency band. If the power values are measured with a constant frequency spacing Δf this results in a constant moving average length M as follows:

$$M = \frac{\Delta f_{NB}}{\Delta f} \quad (14)$$

In this paper the frequency band shall be 160 Hz which leads to $M = 32$. Setting $M = 32$ simplifies the needed scaling in the moving average calculation to a binary shifting which is less time consuming.

III. PROPOSED ALGORITHM

To properly detect multiple peaks simultaneously in the frequency domain on an embedded processor, the algorithm has to be resource efficient and real-time capable. The algorithm shall be resource efficient when it doesn't save more data than necessary and shall process information as soon as possible. It shall be real-time capable if it is possible to run during the control task on the processor and shall not use recursions or loops with unknown runtime.

A. Available Data

The authors have already presented a way to measure an online frequency response in a real-time embedded signal processor [2]. Based on this work the algorithm will capture N samples of the unfiltered current reference signal u in a buffer with a sampling frequency of $f_s = 4\,kHz$. In closed loop the unfiltered control reference signal u offers a good representation of possible resonance frequencies. Furthermore this signal will be notch filtered if required, so only those resonances present in this signal are candidates for filtering.

The frequency identification algorithm will return a data tuple of a measured bandpass power P^k during the last buffer time at frequency f^k. This data tuple $\langle f^k | P^k \rangle$ can be used online to identify peaks.

B. Online Calculation

The algorithm can detect multiple peaks online due to the following principles:

1) Calculate a low-pass filter of the measured power values P^k with an Integrated-Comb filter of length M.

2) Get a measurement for the relative peak P^k_{rel} with respect to the frequency band Δf_{NB}

3) Look for maxima in P^k and keep the R highest peaks in a buffer for later post processing, if $P^k_{rel} \geq \varepsilon$.

P^k_{rel} can be described as:

$$P^k_{rel} = \frac{P^{k-\frac{M}{2}}}{P^k_{LP}} \tag{15}$$

$$P^k_{LP} = \frac{1}{M}\left(w^k - w^{k-M}\right) \tag{16}$$

$$w^k = \sum_0^k P^k \tag{17}$$

To detect a relative maximum at P^{k-1}_{rel} use the necessary requirement:

$$P^{k-2}_{rel} < P^{k-1}_{rel} \wedge P^{k-1}_{rel} > P^k_{rel} \tag{18}$$

The data tuple of the maximum $\langle f^{k-1} | P^{k-1} \rangle$ and the surrounding neighbors $\langle f^k | P^k \rangle$ and $\langle f^{k-2} | P^{k-2} \rangle$ will be saved in a buffer for post processing.

To increase the frequency accuracy the samples adjacent to the maximum can be used to interpolate a quadratic function:

$$\hat{P}(f) = af^2 + bf + c \tag{19}$$

The main interest is the maximum of (19). Due to the equally spaced frequency vector with $\Delta f = const$ the interpolated maximum can be described as:

$$\hat{f}_{Max} = f_2 + 0.5\Delta f \frac{p_3 - p_1}{2p_2 - p_1 - p_3} \tag{20}$$

The measured tuples are arranged such that $\langle f_2 | p_2 \rangle$ is the previously detected maximum and $\langle f_{1,3} | p_{1,3} \rangle$ are the surrounding values.

The parameter Δf will be set to 5 Hz in this paper and the parameter ε shall be in the range of $1.5 \leq \varepsilon \leq 2$.

IV. Simulation

Simulations will be carried out in MATLAB and with a synthetic multisine signal fed to the signal processing system. A multisine signal stimulation can be described as:

$$y(t) = \sum_{k=1}^{3}\left(A_k \sin(2\pi f_k t)\right) \tag{21}$$

The measured power of a signal can be described as:

$$P = \frac{1}{T}\sqrt{\int_T u^2(\tau)d\tau} \tag{22}$$

Using $T = \frac{N}{f_s}$ and $u(t) = A\sin(2\pi f t)$:

$$P = \frac{f_s A}{N}\sqrt{\int_0^T \sin(2\pi f \tau)^2\, d\tau} \tag{23}$$

$$P = \frac{f_s A}{N\sqrt{2}} \tag{24}$$

The used parameters are listed in Table II and the result of the scanned signal in the frequency domain is shown in Fig. 3. Peaks are only recognized when the power sample values are significantly above the frequency band Δf_{NB}. The measured peaks match the theoretical values stated in Table II.

Fig. 4 shows the detected peaks in this signal. The peaks at 500 and 600 Hertz are detected, the signal at 530 Hertz is not detected due to the relative high powered "neighborhood".

TABLE II MULTISINE PARAMETRIZATION FOR SIMULATION ON SIGNAL PROCESSOR

$A_k[Digit]$	10000	5000	20000
$f_k[Hz]$	600	530	500
$P[-]$	47.14	23.58	94.28

IV. Measurements on a Machine

Tests are also performed on a round table with a direct torque motor in a machine where in contrast to the simulation multiple unknown resonance frequencies are present in the system. The motor is connected to a frequency inverter where the implemented software code will be executed. The mechanical plant consists of a chuck system with a mounted pallet with attached workpiece.

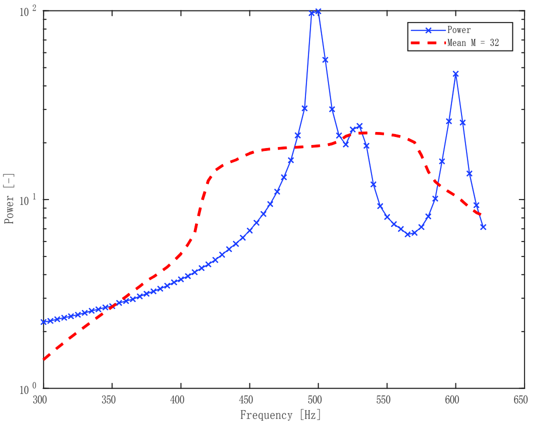

Figure 3 Simulated power of a multisine signal and the corresponding low-pass filter with M = 32 elements.

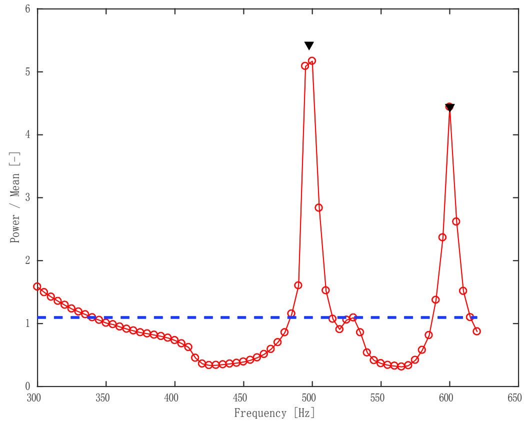

Figure 4 Peak detection of simulation multisine signal with threshold set to mean of power (dashed line).

A. Performance Evaluation Method

The quality of proposed algorithm will be analyzed by measuring the frequency response of the position control loop as already used in [2]. Therefore the position reference signal φ_r is augmented with a PRBS excitation. The transfer function from position reference φ_r to measured motor position φ_M is then calculated by the MATLAB 'tfestimate()'-command, which uses the Welch-Method ([12],[13]).

To reduce the effect of mechanical friction and nonlinearities in the current loop, the round table will be operated at a constant speed reference $\dot{\varphi}_r$. The transfer function will always be calculated for verification of the algorithm after the identification process has finished, thus leading to a stationary process. The displayed coherence is a normalized value indicating the trustworthiness of the calculated transfer function and can be calculated using the MATLAB 'mscohere'-command. For further details see [14].

TABLE III Parameters Used During The Tests With A round Table on A Machine.

Parameter	Value
N	600
f_{Start}	2000 Hz
f_{End}	300 Hz
Δf	5 Hz
$\Delta\omega_{BP}$	Δf
$\Delta\omega_N$	0.3
g_N^1	0.2
f_s	4 kHz
f_{op}	32 kHz
Δf_{MD}	50 Hz
Δf_{NB}	160 Hz

B. Test Procedure

The parameters used to identify the resonance frequencies are listed in Table III. A workpiece is mounted on an ITS-Chuck system by EROWA. This workpiece forms a two-mass system with the round table and thus adds an extra resonance frequency, which can be observed in the actual speed signal $\dot{\varphi}_M$ and in the unfiltered current reference signal u.

C. Test Results

Fig. 5 shows the measured frequency spectrum of the unfiltered current reference signal u. The identified peaks are listed in Table IV. The threshold ε is set to the mean of the power signal, thus discarding some peaks with less effect on the overall machine performance. Especially the mounted workpiece is visible in the peak detector.

Fig. 6 shows the position tracking transfer function of the round table with the attached workpiece. Due to the high resonance amplitude the results in this figure were measured with active notch filter present at 905 Hertz. It can be observed, that the resonance peak is not present in the figure anymore. It would now be possible to increase the overall tracking performance by increasing the controller gains.

TABLE IV Measured Peaks On A Machine.

$f_{Max}[Hz]$	905	1795	1461	477	302
$P_{rel}[-]$	5.8	1.89	1.80	1.80	1.79

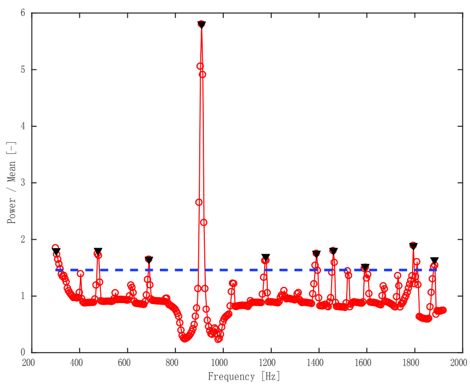

Figure 5 Peak detection of a round table with mounted workpiece. Detection based on control reference signal. Threshold set to 1.5 (dashed line).

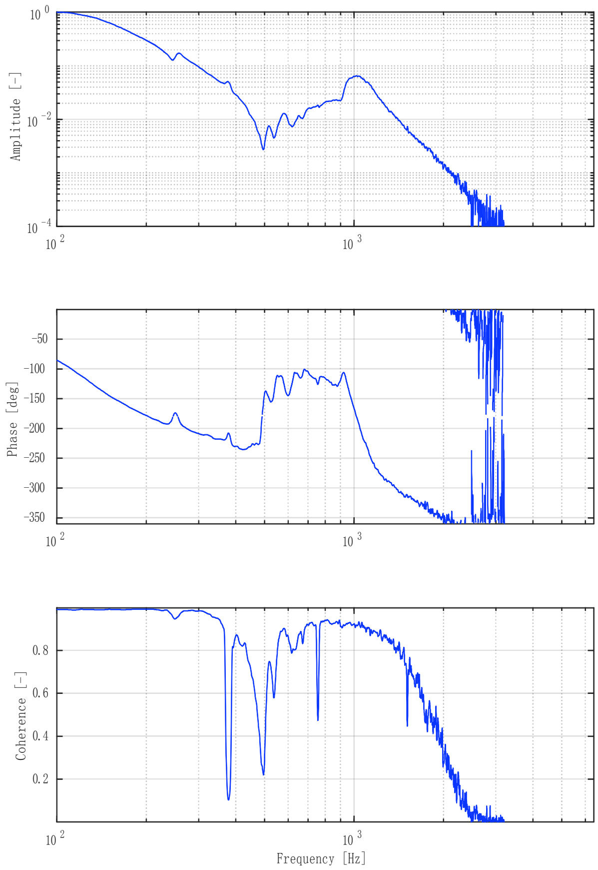

Figure 6 Position tracking transfer function with activated notch filter at 905 Hz.

V. Conclusion

This paper has used the frequency scanning algorithm developed in [2] to detect multiple resonance peaks in a single identification run. The proposed algorithm is a fast, real-time capable algorithm which uses the measured signal power relative to the average signal power in the ”neighborhood”. Therefore it is possible to detect local peaks. Real-time capable means operating during the measurement and processing samples as they enter the system sampled at 32 kHz. Peaks below an user defined threshold ε are discarded online to reduce the needed maxima saved in a buffer for post-processing. To achieve optimal performance the post-processing stage discards peaks too close to another.

The algorithm was tested with a synthetic multisine signal and afterwards transferred to a round table mounted on a machine. It was shown, that multiple resonance frequencies present in the system can successfully be detected with this algorithm. This contribution will improve the productivity of the machine due to a more robust and more accurate tracking performance.

Further works are planned to improve the notch filter width and depth parameter tuning and to develop methods to predict the effectiveness of notch filters.

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He is a PhD Student with the University of the Federal Armed Forces Hamburg, Germany since 2016. His main research interest is the application of control technologies for mechatronic systems. During his work experience as a Research and Development Engineer with a milling machine production company (2007-2016) he focused on researching and implementing control technologies for electrical drives.
Mr. Aldag was awarded for best oral presentation at the ICCMA conference in 2017 for his speech about Multiple Resonance Peak Detection in Servo Drive Applications.